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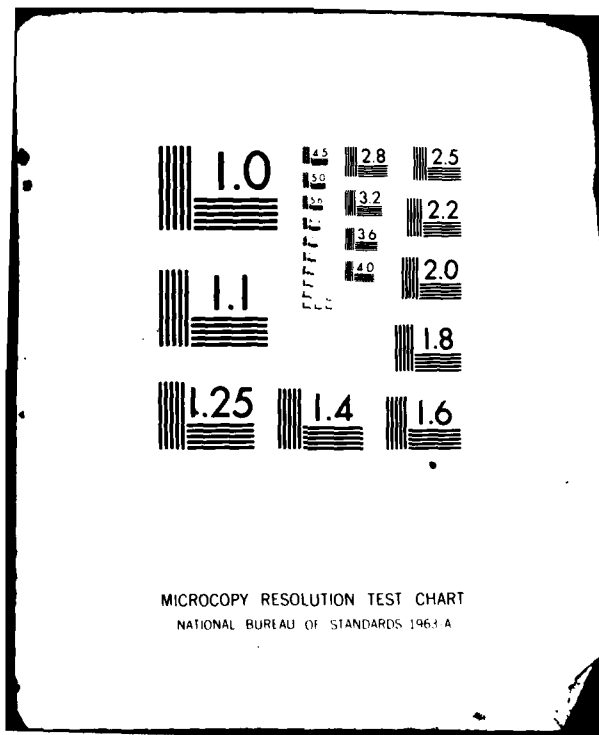
Interim Scientific Report

on

ADVANCED DIAGNOSTICS AND INSTRUMENTATION

FOR CHEMICALLY REACTIVE FLOW SYSTEMS

Contract F49620-80-C-0091

Prepared for

Air Force Office of Scientific Research

For the Period

September 1, 1980 to September 30, 1981

Submitted by

R. K. Hanson, Project Director
D. Baganoff
C. T. Bowman
R. L. Byer
B. J. Cantwell
S. A. Self

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**HIGH TEMPERATURE GASDYNAMICS LABORATORY**
**MECHANICAL ENGINEERING DEPARTMENT**

**STANFORD UNIVERSITY ■ STANFORD, CALIFORNIA**

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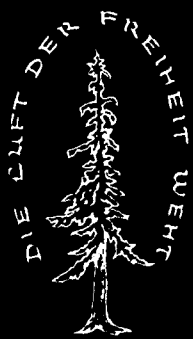September 1, 1980 to September 30, 1981

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| Flame | Infrared | Turbulent | | Ultraviolet |
| Diagnostics | Absorption | Fluorescence | Evaporation | |
| Laser | Raman | Reacting | | |

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Progress is reported for the first year of an interdisciplinary program to investigate and develop modern diagnostic techniques for application to reacting flows. Project areas include: (1) development and application of optical probes for species measurements employing tunable ultraviolet, visible and infrared laser sources; (2) development and application of a coherent anti-Stokes Raman spectroscopy (CARS) system for temperature and velocity measurements in a supersonic jet; (3) development of a computed absorption tomography system for species measurements in a plane using a tunable laser
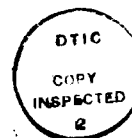
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source; (4) development of a fast-response temperature monitor, based on line-reversal concepts, applicable to particle-laden high temperature flows; (5) investigation of new quantitative flow visualization concepts, including temporally and spatially resolved species measurements in a plane using laser-induced fluorescence; (6) application of modern diagnostic techniques to a two-dimensional reacting shear layer; (7) development of measurement techniques and a novel facility for investigations of droplet evaporation in turbulent flows; (8) investigation of novel variations of tunable laser absorption spectroscopy yielding spatial resolution, including saturation spectroscopy and ac-Stark effect modulation spectroscopy.

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## TABLE OF CONTENTS

## 1.0 INTRODUCTION

Progress is reported for the first year of an interdisciplinary program to investigate and develop modern diagnostic techniques for application to reacting flows. The eight project areas are: (1) development and application of optical probes for species measurements employing tunable ultra-violet, visible and infrared laser sources; (2) development and application of a coherent anti-Stokes Raman spectroscopy (CARS) system for temperature and velocity measurements in a supersonic jet; (3) development of a computed absorption tomography system for species measurements in a plane using a tunable laser source; (4) development of a fast-response temperature monitor, based on line-reversal concepts, applicable to particle-laden high temperature flows; (5) investigation of new quantitative flow visualization concepts, including temporally and spatially resolved species measurements in a plane using laser-induced fluorescence; (6) application of modern diagnostic techniques to a two-dimensional reacting shear layer; (7) development of measurement techniques and a novel facility for investigations of droplet evaporation in turbulent flows; (8) investigation of novel variations of tunable laser absorption spectroscopy yielding spatial resolution, including saturation spectroscopy and ac-Stark effect modulation spectroscopy.

## 2.0  PROJECT SUMMARIES

Included in this section are summaries of progress in each of the eight project areas.  Each project summary contains the following subsections: (a)  Introduction;  (b)  Scientific Merit;  (c)  Status Report;  (d) Publications and Presentations;  (e)  Personnel

### 2.1  Tunable Laser Absorption Probes
#### Introduction

The development of new techniques for the measurement of gaseous species concentrations with temporal and spatial resolution is widely recognized as critical to the development and validation of fundamental models of turbulent combustion and computational models of practical combustors.  Techniques completely suitable for these purposes are not yet available, although research is actively underway in several laboratories to develop these measurement tools.  One approach which we have pursued at Stanford utilizes absorption spectroscopy as the physical sensing process with tunable, narrow-linewidth cw lasers as radiation sources.  This approach shows considerable promise for use in a variety of diagnostic configurations, depending on measurement requirements, and for a wide range of species and concentrations.

Our work in this area has led to the first use of tunable infrared diode lasers to measure species concentrations and gas temperature in combustion gases.  The techniques developed are both sensitive and simple.  In most cases the laser wavelength is rapidly modulated and fully resolved absorption line profiles are recorded.  An important advantage of this approach is its insensitivity to the presence of particles or droplets in the flow, which may be particularly important in the analysis of droplet or solid fuel combustion flows.  Within the past few years, our experiments have demonstrated the high accuracy and sensitivity possible with this technique for NO, CO and temper-ature in steady, fluctuating and sooting flames.  This work has included the first known measurements of fundamental line strength and lineshape parameters of infrared absorption lines under combustion conditions.

Our success with tunable diode laser spectroscopy, which is suitable only for infrared-active species, has prompted us to initiate similar research

utilizing recently developed tunable ring dye lasers. This new laser, which provides tunable, cw single-frequency output at ultraviolet and visible wavelengths is better suited for detection of free radical species. The diode and dye laser research is thus complementary in that both radical species and stable infrared-active species can now be monitored.

During the past year, we have directed our work towards alleviating the major objection to absorption spectroscopy as a diagnostic technique, namely that the spatial resolution is often insufficient. Our approach has been to design "absorption probes", devices with variable absorption path length which can be conveniently inserted into combustion flows (even when optical access is limited) to yield the required spatial resolution. Our objective, in simple terms, is to combine most of the advantages of tunable cw laser absorption spectroscopy -- accuracy, simplicity, species specificity, discrimination against particulates, and temporal resolution -- with the advantages of probe techniques, particularly spatial resolution and applicability to remote operation in devices with poor optical access. The basic concepts of these various first-generation probes are shown in Figs. 1-4.

Figure 1 indicates a novel laser absorption sampling probe now under development for use with the diode laser. In essence, this is a conventional sampling microprobe with a miniature in-line absorption cell. The effective spatial resolution is a few millimeters, depending on probe conditions and cell length, and the effective temporal resolution is less than one millisecond. Thus this new scheme promises to provide real-time measurements of ir-active species with millimeter spatial resolution, kilohertz frequency response, and sensitivity down to about 100 ppm (for CO and other comparably strong ir absorbers).

Figure 2 shows another absorption probe being developed for use with the diode laser. This probe also provides high spatial resolution (≈ 3-5 mm) and temporal resolution (≈ 10 kHz), but is designed to measure in situ rather than in sampled gases. Such an approach is preferable when the species are unstable and are likely to undergo conversion during sampling.

Figures 3 and 4 summarize our current approach to develop a combined absorption/fluorescence probe for use with a tunable ring dye laser. The

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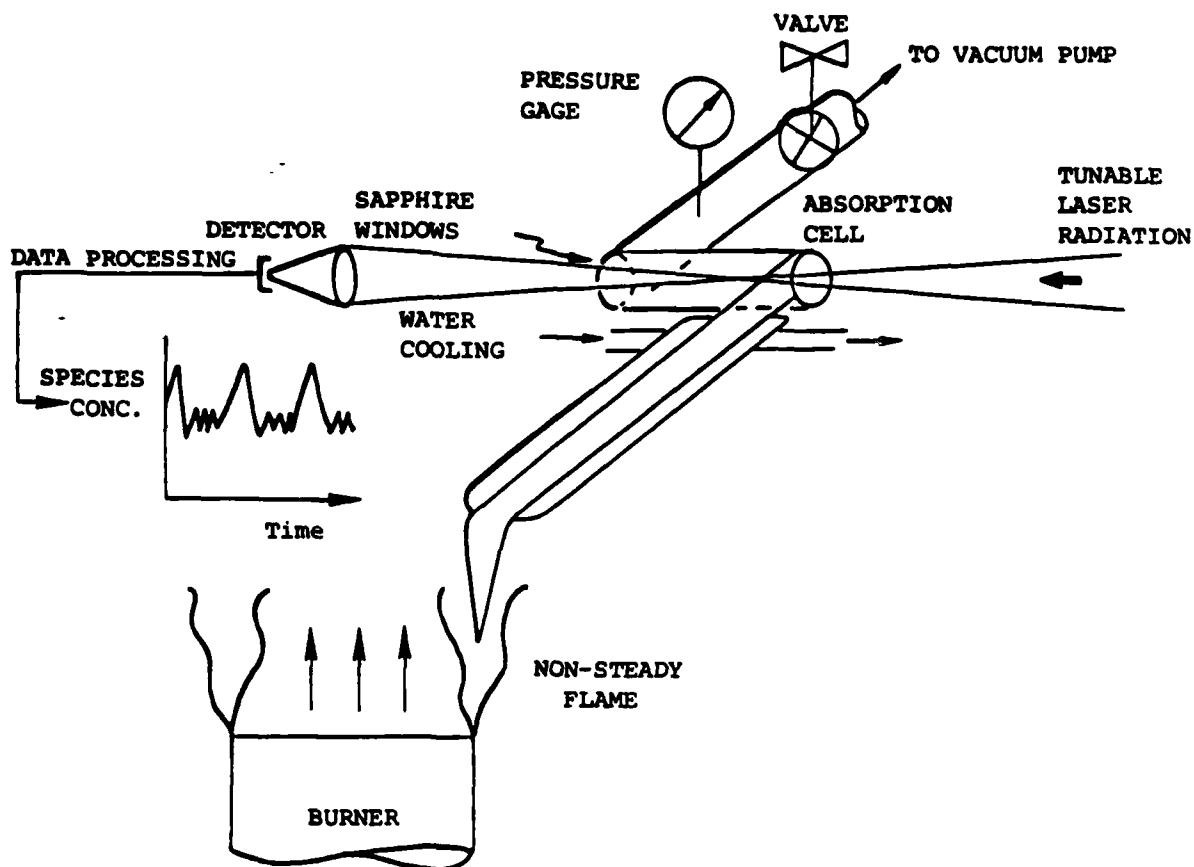
Objective: Develop sampling probe with in-line absorption
analysis for temporally and spatially resolved
species measurements

Status: First-generation probe employing a cw tunable IR
diode laser has been built

Disadvantages: Intrusive

Advantages: Superior sensitivity and accuracy
Applicable where optical access is restricted
Yields continuous, real-time recording of species
concentration

Figure 1. Laser absorption sampling probe for temporally and spatially
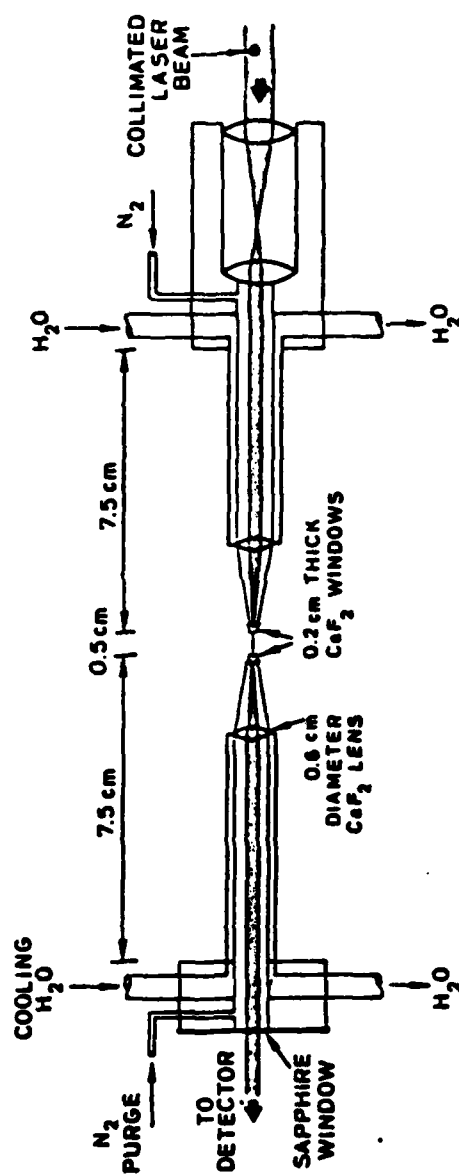resolved combustion measurements.

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Figure 2. Schematic of infrared optical probe for spatially resolved in situ measurements.
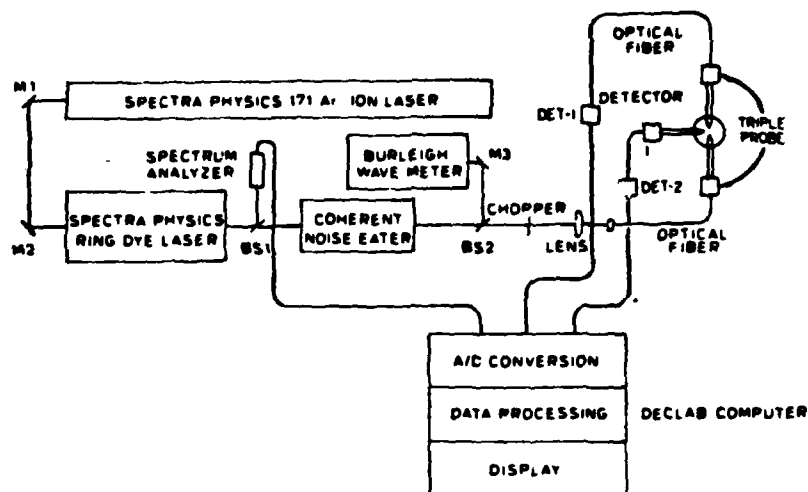
**Figure 3.** System for remote, spatially defined sensing of chemical species using tunable laser absorption/fluorescence spectroscopy.
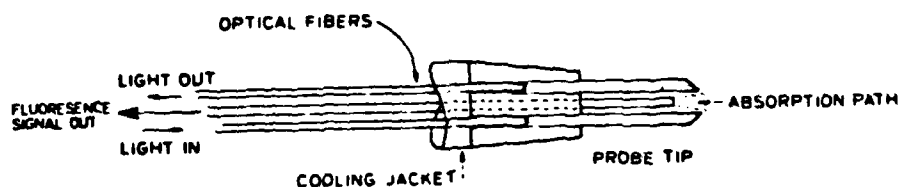


**Figure 4.** Alternative probe configuration.

Significance:   First fully resolved atomic absorption line profiles in flames
                    Enables fundamental studies of lineshape phenomena at
                    high temperatures
                    Combines advantages of absorption and fluorescence
                    Potential major impact on chemical kinetics – Technique
                    applicable to static and flow reactors, laboratory flames
                    and plasmas
                    Applicable to hostile, two-phase flows with limited
                    optical access
                    Species specific, sensitive, quantitative detection

Disadvantages:  Intrusive
                    Minimum spatial resolution (for flames) ~ 2 mm

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overall experimental set-up is depicted in Fig. 3; an improved candidate probe
configuration is shown in Fig. 4. The objective of this work is similar to
that with the diode laser, namely to exploit the ability of the laser to
measure species concentrations (or temperature) by absorption in a configu-
ration which yields spatial resolution and lends itself to remote operation.
In addition, by adding capability for simultaneous fluorescence measurements,
the detection range of the device is increased substantially. The wavelength
range accessible with this device is approximately 280-750 nm, and so we have
been able to implement optical fibers into our present design. Recent
research has been concerned with establishing suitable: (1) fiber and probe
configurations; (2) laser stabilization and modulation schemes; and (3) data
recording and processing schemes.


## Scientific Merit

This research seeks to provide sensitive, species specific techniques for
monitoring gaseous concentrations in reacting flows with high spatial and
temporal resolution. Satisfactory techniques are not currently available and
hence the development of such devices has the potential for significant impact
on various scientific and engineering aspects of combustion and propulsion.
Our approach is unique in that it seeks to combine recently developed tunable
single-frequency sources with novel absorption probes. The resulting diagnos-
tics will be well suited to meet a variety of practical measurement require-
ments and also for use in fundamental studies of lineshapes and line strengths
of combustion gases. For example, work at Stanford to measure lineshapes in
high temperature gases has resulted in the first reported fully resolved
infrared absorption lines in both flame gases and in shock-heated gases.

There are at present no competitive approaches which yield comparable
real-time, continuous records of species concentration. The pulsed laser
techniques of laser-induced fluorescence (for radical species and CARS (for
major species) yield similar or better spatial resolution without requiring an
intrusive probe, but these techniques are less direct, suffer from large
uncertainties and complex data analysis, yield only low repetition rate
measurements, and are more demanding with regard to optical access.

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## Status Report

For purposes of this discussion, the work can be divided into two topics: (1) tunable diode laser absorption/fluorescence spectroscopy; (2) tunable dye laser absorption/fluorescence spectroscopy.

### (a) Tunable Diode Laser Absorption Spectroscopy

During the past 12 months two absorption probes have been constructed and tested: a variable path length, intrusive absorption probe with miniature optical elements (see Fig. 2); and a fast sampling probe with a miniature in-line absorption cell (see Fig. 1). These probes are designed to be used in conjunction with tunable diode lasers and to yield both spatial and temporal resolution. To our knowledge, these are the first such probes to have been developed, and they offer prospects for a variety of pioneering basic and applied measurements in combustion flows. We have also worked to develop an absorption probe with a fiber optic link between the probe and the tunable diode laser source, but have not yet found a suitable fiber material.

A more detailed schematic of the current electro-optical arrangement is shown in Fig. 5. Results indicating the type of data which can be obtained are shown in Fig. 6, in this case with the fast-sampling probe. This is a real-time recording of the transmitted laser intensity with the laser tuned to the center of a specific CO absorption line and with the probe fixed at a point in the flame zone of a turbulent CO/air diffusion flame. These data are fed to a computer which digitizes the data and converts each point to a value for the CO mole fraction. Subsequently the data can be manipulated to obtain probability distribution functions, as shown in Fig. 7, or to obtain a frequency power spectrum.

To our knowledge, these are the first fully time-resolved molecular species measurements obtained in a flame. The effective spatial resolution is about 5 mm; the temporal resolution is less than 1 millisecond. The simplicity and accuracy of these techniques together with their applicability to a wide variety of infrared-active species and to a range of dirty and hostile combustion flows, suggests that this is a significant diagnostics development. The data will be of use to turbulent flow and combustion modellers and also to combustion scientists engaged in studies of practical devices.
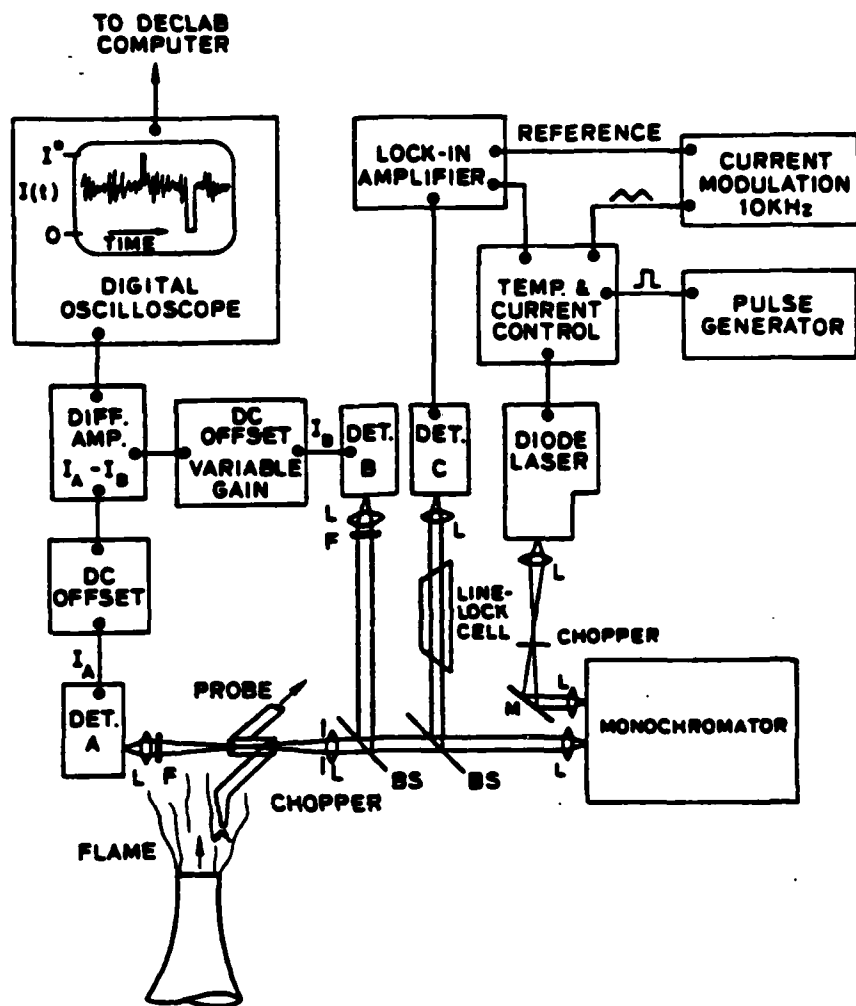
Figure 5. Schematic diagram of experimental set-up for
tunable infrared laser absorption probes in a CO/air
turbulent diffusion flame. Either the sampling probe
on the _in situ_ can be inserted at the measurement location.

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Figure 6. Raw data for laser transmittance from fast sampling absorption probe at a point in the flame zone of a CO/air turbulent diffusion flame.

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Figure 7. Radial map of probability density functions of CO mole percent in CO/air turbulent diffusion flame at an axial position X/D = 2. a) based on sampling probe data, b) based on in situ probe data.

(b) Tunable Dye Laser Absorption Spectroscopy

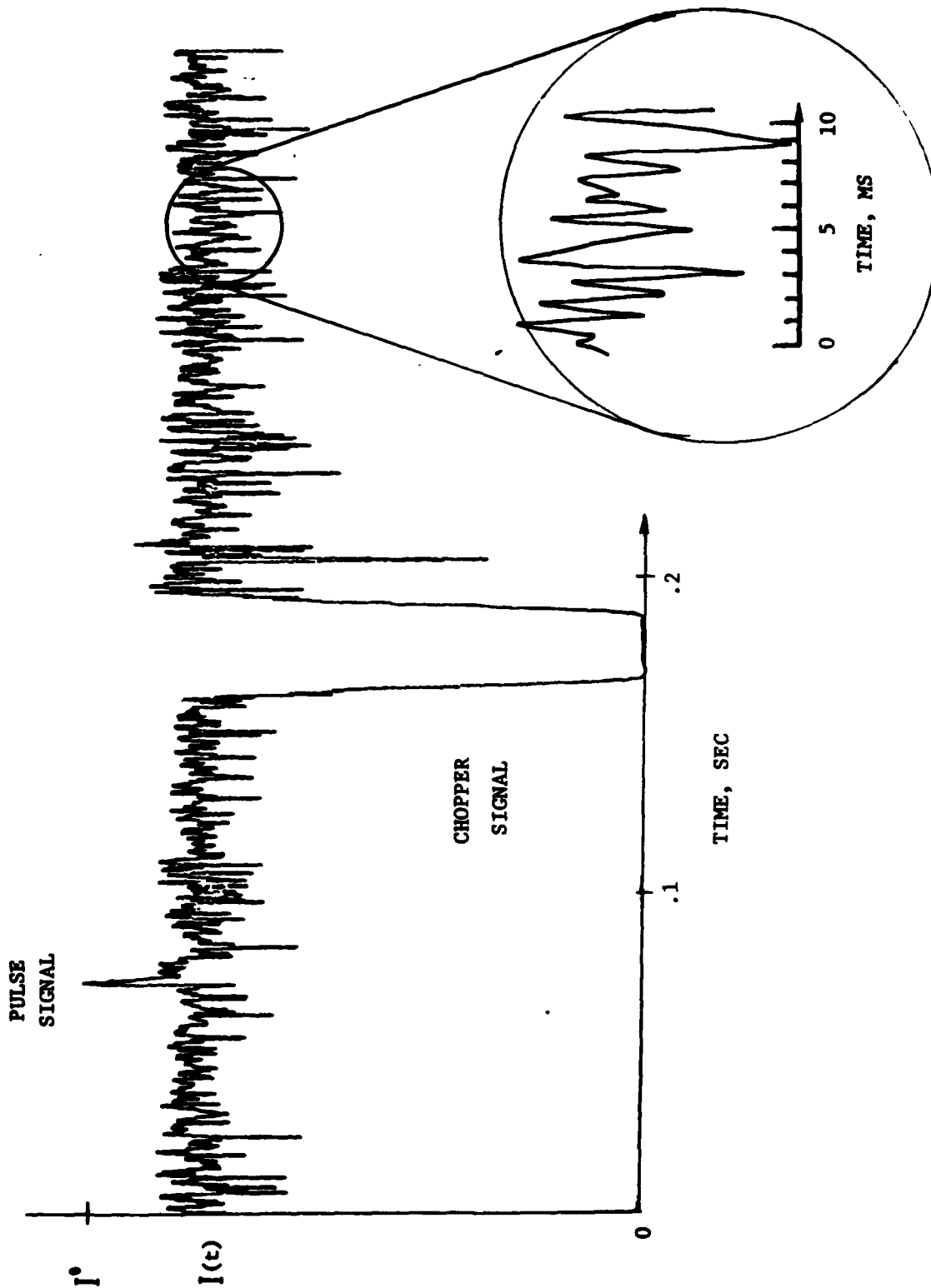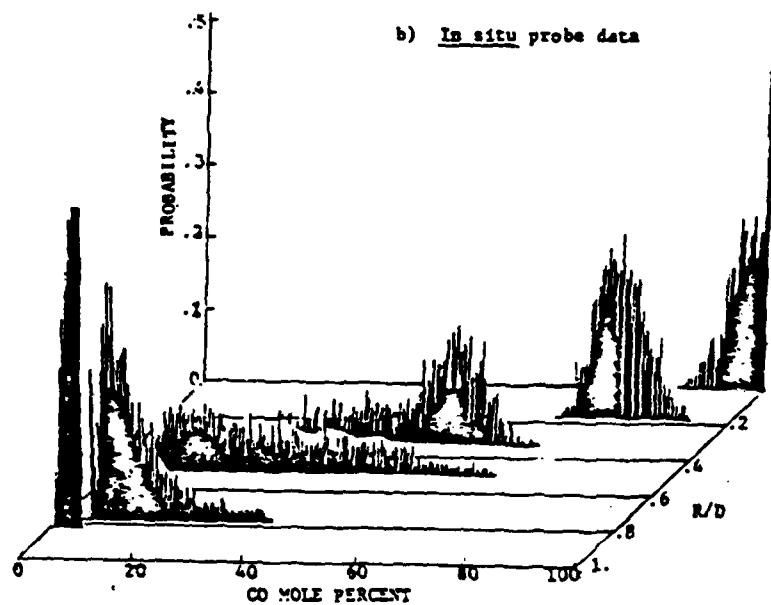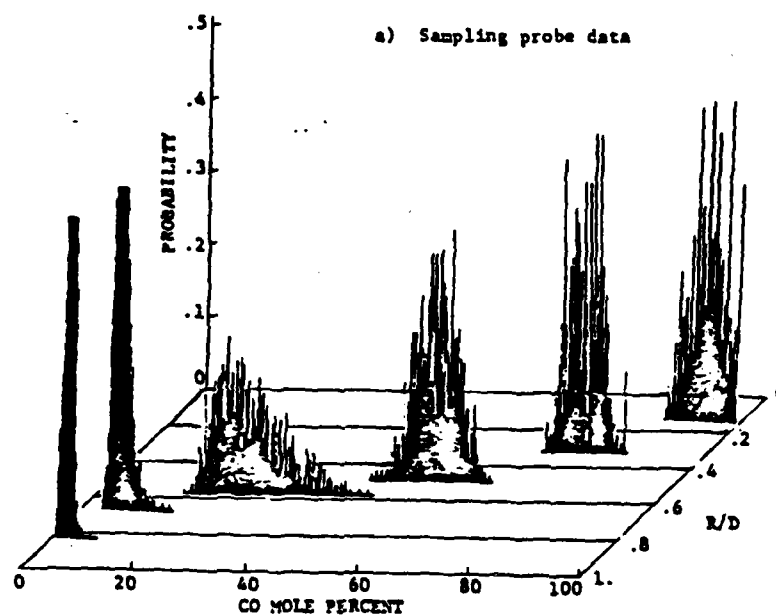During the past year we have made progress on several aspects of this project, and critical results have already been presented and submitted for publication. Work has included:

1. design, construction and testing of a first-generation optical absorption/fluorescence probe using 1 mm fused silica fiber optics.

2. development of hardware and software to modulate the dye laser wavelength, transfer detector signals to a dedicated laboratory microcomputer, and process data to recover fully resolved absorption line profiles, temperature and species concentrations.

3. assembly and testing of an external frequency doubling system to shift the tunable laser output into the ultraviolet.

4. laser absorption/fluorescence probe measurements of Na in a flat flame burner to establish the influence of probe gap on the inferred Na number density and to determine the minimum effective probe path length.

5. laser absorption probe measurements of OH in a flat flame burner using tunable, cw frequency-doubled laser radiation.

Typical results showing absorption/fluorescence probe measurements of Na in a flat flame are shown in Fig. 8. These signals are fed directly to a dedicated computer for on-line analysis yielding Na number density and best-fit line shape parameters.

The results of an investigation of the influence of absorption path length are shown in Fig. 9. These measurements were made in a uniform field of Na above a flat flame. The quantity plotted is proportional to the inferred Na number density, so that the fall-off in the curve indicates the minimum acceptable probe spacing, about 3 mm, which is more than adquate for purposes of many combustion measurements.

The use of a combined absorption/fluorescence probe extends the dynamic range of the probe. When sufficient absorption occurs, the absorption data can be used directly. At lower levels of concentration (and absorption), the fluorescence probe can be used, after having been conveniently calibrated in situ with the absorption probe. Initial results demonstrating the linear dependence of the fluorescence signal with Na concentration, and the resulting
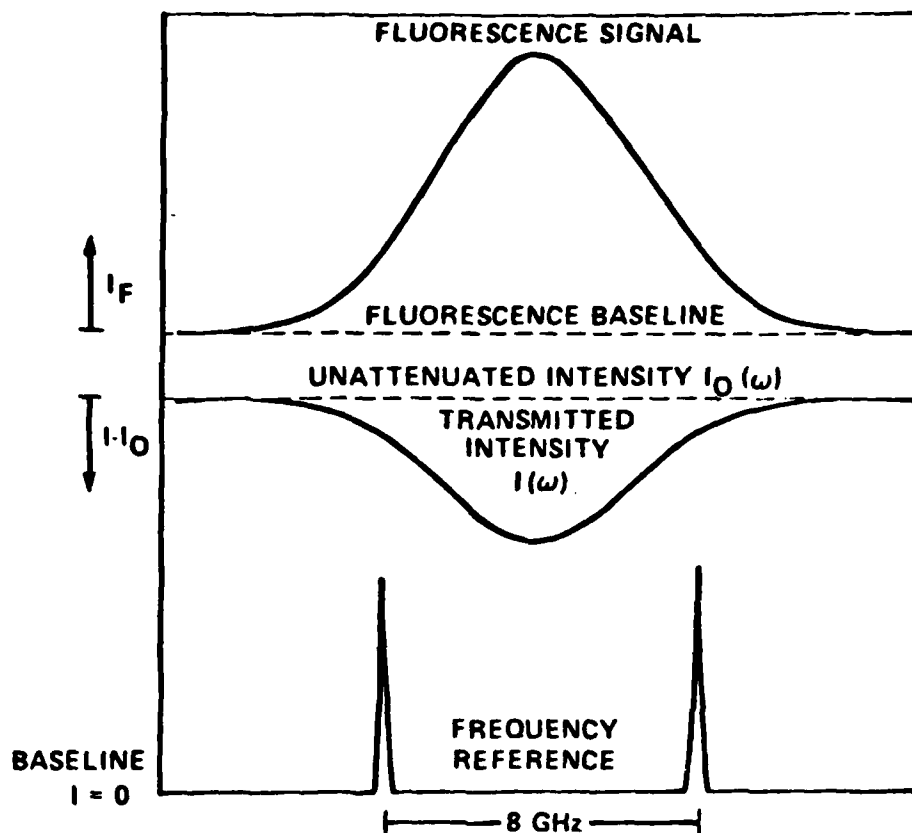
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Figure 8. Typical trace showing sodium absorption and fluorescence in the gases above the flat flame burner.
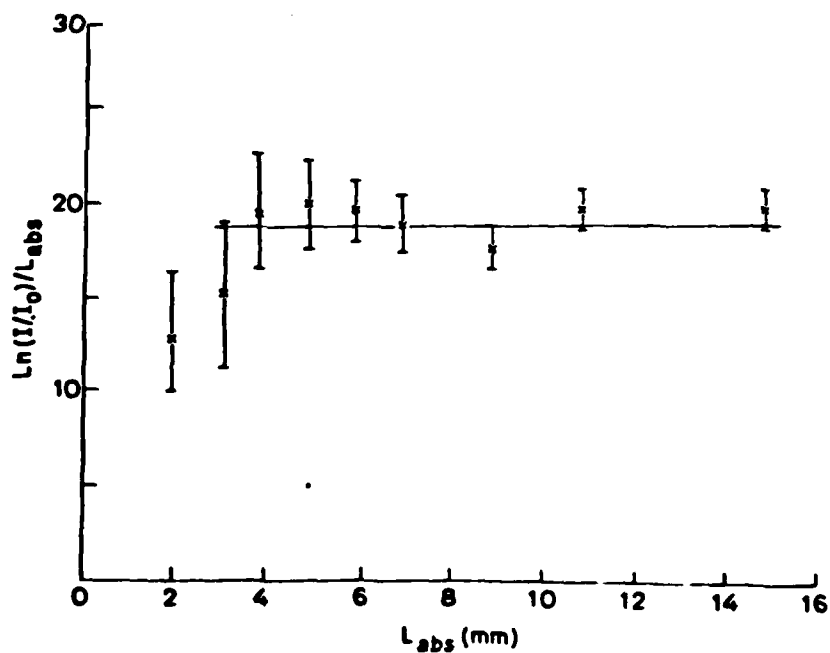


Figure 9. Graph of $\ln(I(\omega)/I_0(\omega))/L_{abs}$ vs absorption path length.

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calibration, are shown in Fig. 10. Extension of the measurements to lower concentrations, below the range accessible with the absorption probe, is demonstrated in Fig. 11.

Finally, application of the probe to spatially resolve the Na concentration field above a single grain of salt located on the burner surface is indicated in Figs. 12 and 13, thereby confirming the utility of this probe to provide spatially resolved species measurements.

## Publications and Presentations

### Presentations

1.  G. Kychakoff and R. K. Hanson, "Optical Fiber Probe Using Tunable Laser Absorption Spectroscopy for Combustion Measurements," presented at 1981 Los Alamos Conference on Optics, April 1981.

2.  S. M. Schoenung and R. K. Hanson, "Laser Absorption Sampling Probe for Spatially and Temporally Resolved Combustion Measurements," to be presented at 1981 Conference on Lasers and Electro-Optics, Washington, June 1981.

### Publications

1.  S. M. Schoenung and R. K. Hanson, "CO and Temperature Measurements in a Flat Flame by Laser Absorption Spectroscopy and Probe Techniques," Combustion Science and Technology 24, 227-237 (1981).

2.  G. Kychakoff and R. K. Hanson, "Optical Fiber Probe Using Tunable Laser Absorption Spectroscopy for Combustion Measurements," to be published in Proceedings of 1981 Los Alamos Conference on Optics.

3.  S. M. Schoenung and R. K. Hanson, "Laser Absorption Sampling Probe for Spatially and Temporally Resolved Combustion Measurements," submitted for publication in Applied Optics, April 1981.

## Personnel

| | |
|---|---|
| Ronald K. Hanson | Adjunct Professor and Director of Diagnostics Institute |
| George Kychakoff | Graduate Student, Mechanical Engineering (Ph.D. expected in June 1982) |
| Susan Schoenung | Graduate Student, Mechanical Engineering (Ph.D. expected in June 1982) |

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**Figure 11.** Graph of fluorescence measurements at low sodium densities.



**Figure 10.** Graph of sodium fluorescence vs absorption.

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CONCENTRATION IS IN UNITS OF $10^{12}$cm$^{-3}$

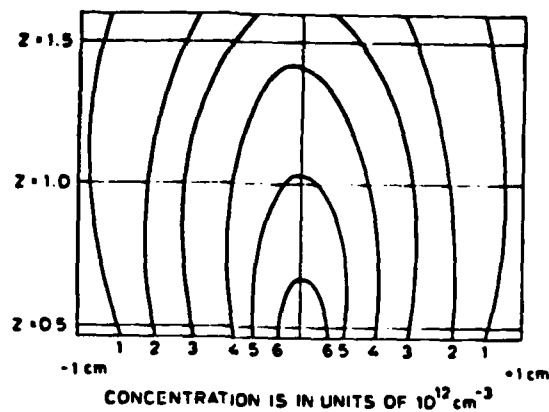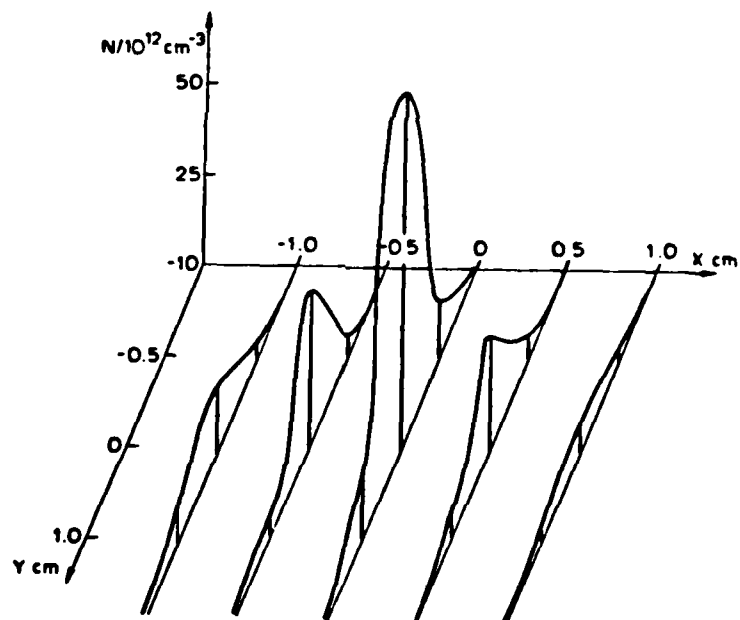**Figure 12. Sodium concentration contours above salt grain located at z = 0.**



**Figure 13. Sodium concentration above salt grain in Z = 0.5 cm plane.**

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## 2.2 Coherent Anti-Stokes Raman Spectroscopy (CARS)

### Introduction

The objective of this aspect of the program is to develop innovative laser spectroscopic techniques to supersonic and combustive turbulent flows. During the first year we have successfully utilized the Coherent Anti-Stokes Raman Spectroscopic (CARS) technique to measure temperature and velocity in a supersonic jet flow. We have, in addition, used the same apparatus to measure density in the flow by an induced fluorescence technique. This latter measurement method led to a joing Applied Physics/Astronautics Ph.D. research program that culminated in the recent Ph.D. of Jim McDaniel.

### Scientific Merit

CARS spectroscopy has been increasingly used as a diagnostic probe for combustion and fluid flow studies. Our work on high resolution CARS in supersonic jets has led to a new understanding of the CARS process in cold expansion flows. We have demonstrated the highest resolution Raman spectra ever achieved. We have measured velocity and temperature to high accuracy in the flow, and we have completed a detailed theory for transit time broadened CARS in a supersonic flow. This latter work is the basis for the Ph.D. thesis of Eric Gustafson.

The combination of high resolution laser sources and supersonic expansion cooled molecular flows has now been recognized as an important advance in laser spectroscopy.

### Status Report

We have completed measurements of temperature and velocity using cw CARS in a Mach 5 supersonic flow, (see Fig. 14). The results were presented at the C.L.E.O.S. Conference in June 1981.[1] We have submitted for publication our velocity measurement work,[2] and we are preparing a publication describing the theory of transit time broadening in CARS. Spectra are illustrated in Fig. 15.
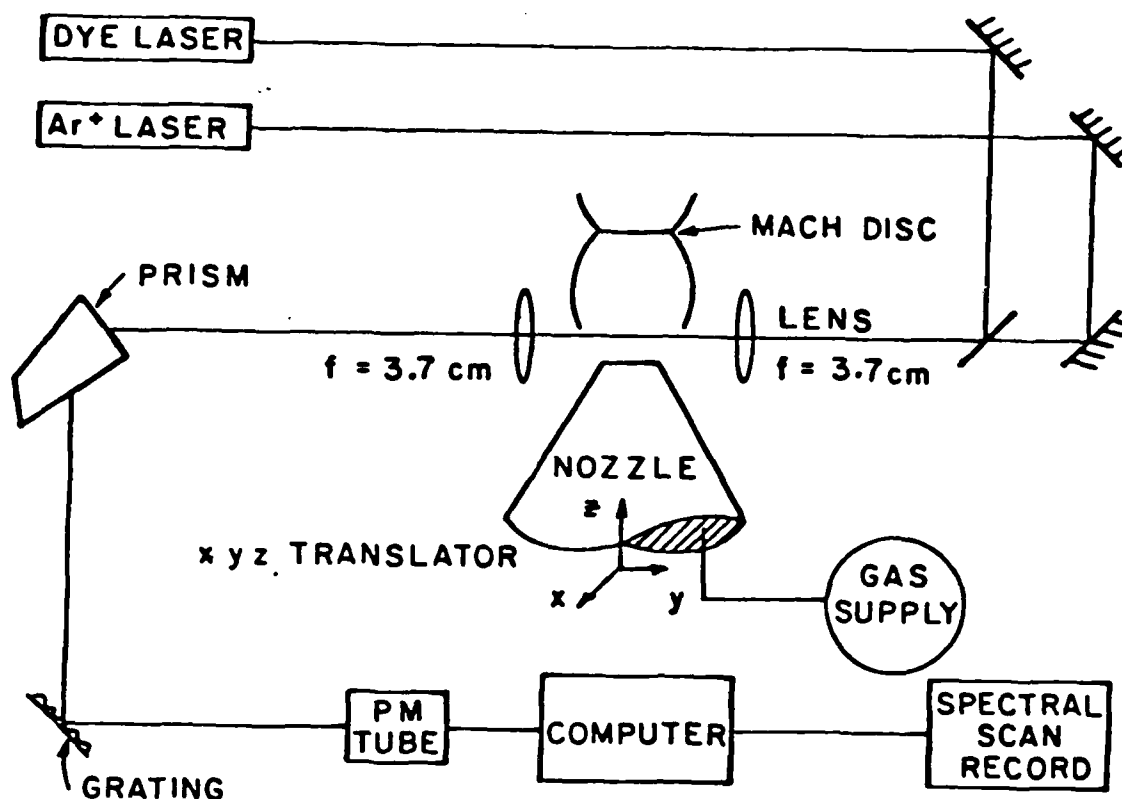
OBJECTIVE: DEVELOP NON-INTRUSIVE DIAGNOSTIC FOR SPATIALLY
RESOLVED TEMPERATURE, PRESSURE AND VELOCITY

DEVELOP GASDYNAMIC-OPTICAL TECHNIQUES FOR SUB-DOPPLER
HIGH-RESOLUTION RAMAN SPECTROSCOPY

STATUS: FEASIBILITY DEMONSTRATED

Figure 14. Supersonic jet CARS spectroscopy.

SPECTRAL SCANS



MACH DISC

NOZZLE

AS THE TEMPERATURE
DECREASES THE LINE
WIDTH DECREASES AND
THE LOWER J LEVELS
ARE PREFERENTIALLY
POPULATED

SIGNAL CPS

$J = 2$  $J = 1$  $J = 0$  T = 54°K
P = 9.2 Torr
M = 5.2

DYE LASER FREQ, GHz

T = 77°K
P = 38.5 Torr
M = 4.1

T = 95°K
P = 85 Torr
M = 3.6

$\Delta W$

T = 54°K
P = 9.2 Torr
M = 5.2

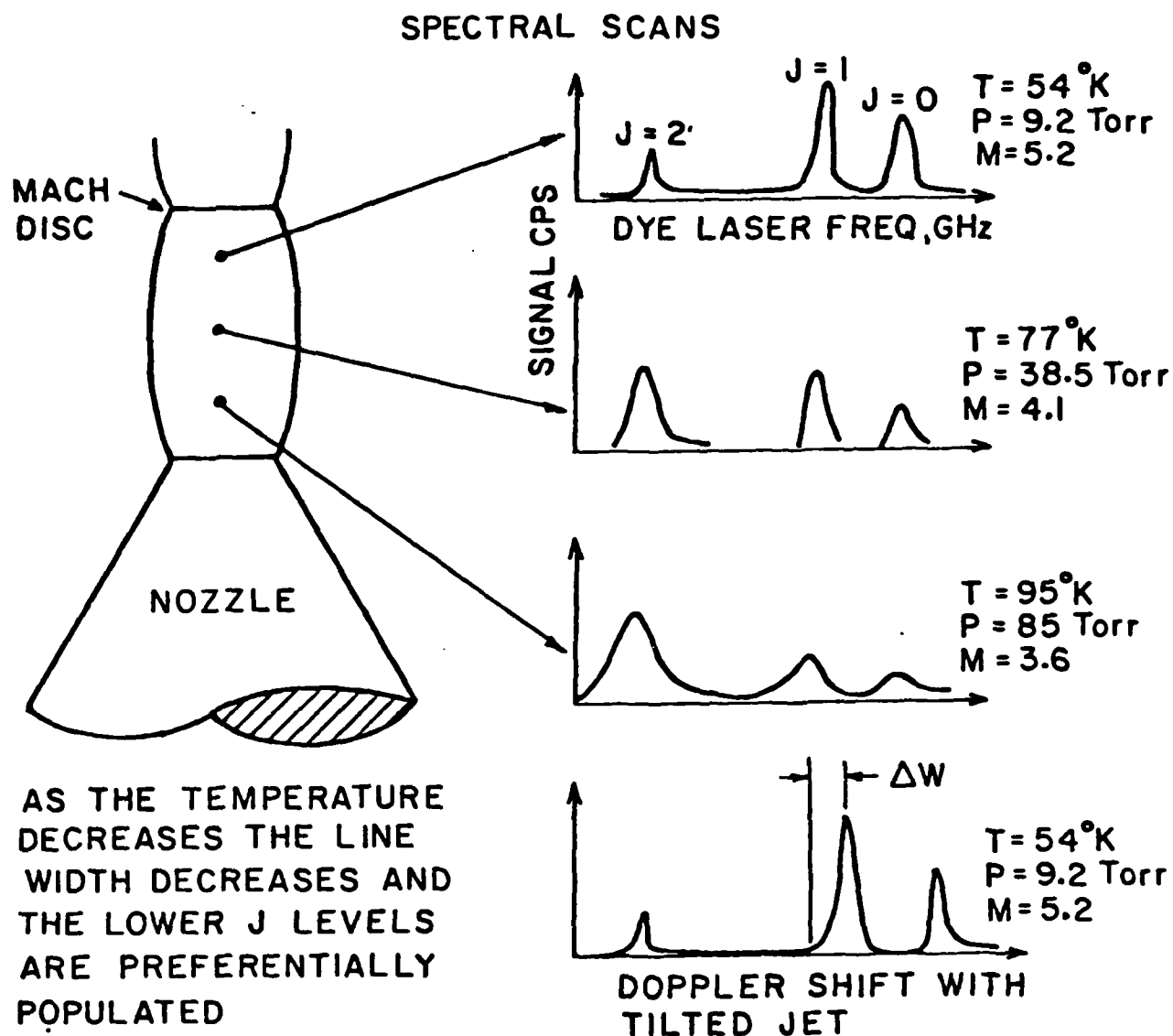DOPPLER SHIFT WITH
TILTED JET

Figure 15. Schematic of the supersonic jet expansion showing the location of
the CARS measurements along the jet axis.  cw CARS spectra of $CH_4$ Q-branch at
the temperature indicated.

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We have described our CARS spectroscopic studies of $CH_4$ in the supersonic flow at the Laser Spectroscopy Conference and have prepared a manuscript for publication.[3] Part of the work described in that paper was the cw CARS measurements in the supersonic flow.

In conjunction with the above work, we have completed density measurement studies in an $I_2$ seeded flow by a detuned fluorescence method. This work is described elsewhere in this report. However, it was performed on the apparatus used in the cw CARS studies and led to the Ph.D. thesis of Jim McDaniel.

During the past year we have also worked on a single axial mode Nd:YAG source for use as a local oscillator for high resolution CARS spectroscopy studies, for high resolution $I_2$ fluorescence studies, and for flow velocity measurements by laser doppler velocimetry.

The source is now operating in both a cw mode and a pulsed mode. Line-width measurements are in progress. The laser is expected to produce 1W of peak power in 1 μsec long pulses at less than 1 MHz linewidth. The 1W power is to be amplified in a Nd:YAG amplifier system to 3 MW of peak power or 300 mJ of energy at 10 pps.

When frequency doubled into the green, this laser source will pump a tunable dye laser and be used for very high resolution CARS spectroscopy studies. In addition, we plan to loan a second Nd:YAG oscillator to General Motors Research Laboratories for high resolution measurements of $O_2$ and atomic oxygen in a controlled flame. This work is in cooperation with Dr. Richard Teets of General Motors.

## Publications and Presentations

### Presentations

1. E. Gustafson, J. McDaniel and R. L. Byer, "Continuous Wave CARS Measurements in a Supersonic Jet," paper W01, C.L.E.O. Conference, June 1981, Washington, D.C.

2. R. L. Byer, M. Duncan, E. Gustafson, P. Oesterlin and F. Konig, "Pulsed and cv Molecular Beam CARS Spectroscopy," presented at the International Laser Spectroscopy Conference, July 1981, Jasper, Canada.

Publications

1. E. Gustafson, J. McDaniel and R. L. Byer, "Continuous Wave CARS Measurements in a Supersonic Jet," to be published in IEEE Journ. Quant. Electr. December 1981.

2. R. L. Byer, M. Duncan, E. Gustafson, P. Oesterlin and F. Konig, "Pulsed and cw Molecular Beam CARS Spectroscopy," to be published in proceedings of the Laser Spectroscopy Conference.

## Personnel

Robert L. Byer            Professor and Chairman
                                     Applied Physics Department

Eric Gustafson           Graduate Student, Applied Physics
                                     (Ph.D. expected in January 1982)

Jim McDaniel             Graduate Student, Aeronautical and
Astronautics

                                     (Ph.D. expected in December 1981)

Sun Yun Long             Visiting foreign scholar
Dr. Sun is working on the    North China Institute of Electro-Optics
single frequency
Nd:YAG source.

## 2.3 Computed Absorption Tomography

### Introduction

The imaging and potential benefits of laser tomography to combustion diagnostics were summarized in the original proposal. Discussions with researchers in combustion diagnostics and fluid flow visualization research have confirmed our original assumption that tomographic images are indeed very useful.

We have learned that General Motors Research Laboratories is very interested in applying tomography to the study of internal combustion engine processes. Discussions are in progress to initiate a joint research effort between General Motors and Stanford University in this area. We feel that such joint research efforts are beneficial to both industry and to the university and that they provide a focus for the research effort on problems that are of current interest.

## Scientific Merit

The goal of our tomography effort is to apply tunable laser sources and tomographic image technology to the study of combusting flows. The interest stems from the potential for inferring the distributions of temperature, density and species concentration in a plane. The visualization of these parameters is very important for the understanding of complex conditions that occur in real combustion systems. A better knowledge of turbulence and combustion on more complex combustors should lead to improvements in the design of combustors for both improved efficiency and longer operational life.

## Status Report

During the past year we have made substantial progress in implementing laser tomography measurements. Briefly, we have received and installed a PDP11/44 computer, the AED color display monitor, the high speed Versatec graphics printer and the CAMAC 4 MHz A/D system. We have installed the computer software system and have transferred our earlier tomography reconstruction programs to the PDP11/44.

We have written display driver progams and have generated color tomographic images from our model programs on the color display unit. We have written software for axial tomography image reconstruction that will be useful for pulsed tomography.

We are writing interface software for the A/D converters and the CAMAC dataway. We have identified, tested and purchased the detectors, amplifiers and multiplexers for the tomography image circle. Our goal is to demonstrate tomographic imaging in well known flow systems using cw laser sources. Our first measurement system will use $I_2$ seeded flows and the available argon ion laser source for absorption tomography studies.

We feel that we have made substantial progress in tomography during the short time since the installation of the computer system. We remain very positive about the use of laser tomography as a new combustion diagnostic tool.

We propose to set up and make cw laser tomography measurements using 100 silicon diode detectors in a fan beam geometry array. This work is proceeding as rapidly as programming, interfacing and electronics assembly allows. The

goal is to complete initial measurements by the end of the first year and to complete detailed studies early in the second year.

Following the cw laser tomography measurements we propose to investigate pulsed laser tomography using axial beam geometry and reticon diode arrays. The pulsed laser sources allow generation of wavelengths from the ultraviolet to the infrared so that a wide range of atomic and molecular species can be probed. Pulsed laser tomography studies should provide very useful time-resolved, two-dimensional images of combusting flows. This aspect of the program will continue for the duration of the second year.

## Publications and Presentations

### Publications

1. D. C. Wolfe and R. L. Byer, "Model Studies of Laser Absorption Computed Tomography for Remote Air Pollution Measurements," submitted to Applied Optics.

### Presentation

2. R. L. Byer, "Laser Tomography for Combustion Diagnostics," General Motors Research Laboratory Colloquium, November 13, 1980.

## Personnel

| | |
|---|---|
| Robert L. Byer | Professor and Chairman Applied Physics Department |
| David C. Wolfe | Post Doctoral Student |
| Keith Bennett | Graduate Student, Applied Physics |
| Greg Farris | Graduate Student, Applied Physics |

## 2.4 Packaged, Fiber Optic Temperature Measuring Instrument
### Introduction

The measurement of gas temperatures by the spectroscopic line-reversal method is an old established technique which has been widely used at Stanford on MHD and other combustion flows. However, hitherto, a suitable optical set up utilizing mirrors, lenses and a grating monochromator has been assembled on an optical bench for each individual application. Not only does this result

in a bulky system, but the techniques employed have given only slow, time-averaged measurements. We believe that by using state-of-the-art components, including optical fibers, narrow-band filters and fast choppers, together with a microcomputer it should be possible to devise a compact, self-contained temperature measuring instrument with fast time response, to ∼ 1 msec.

Schematics of the optical and electronic systems is shown in Fig. 16. All the components enclosed in the block outline (Fig. 16a) will be assembled in a box or cabinet mounted remotely from the combustion system under study. Transmitting and receiving fibers lead to the system, and terminate in cooled, purged tubes or probe tips containing small collimating lenses which would be designed specifically to suit the rig under study. Depending on the application, these transmitting/receiving optics assemblies may be located outside the flow to give line-of-sight average temperaure, or may be ganged together for use as a movable, immersible probe for local measurements.

By using a reference path identical to the measuring path, a beam splitter B, and two synchronized, miniature choppers $C_1$, $C_2$, each detector $D_1$, $D_2$, sees a repetitive sequence of three signals, namely $S_L$ from the tungsten ribbon lamp, $S_G$ from the gas and $S_{L+G}$ from the gas transilluminated by the lamp.

It is possible to show that the gas temperature $T_G$ is given in terms of the brightness temperature $T_L$ of the lamp and these three signals by the formula

$$T_G = T_L \left[ 1 - \frac{T_L}{C_2} \ln \left( \frac{S_G}{S_G + S_L - S_{L+G}} \right) \right]^{-1} ,$$

where $C_2 = 1.438$ cm-K is the second radiation constant.

The signal processing electronics and chopper control circuits are shown in Fig. 16b. The output of each detector feeds into a channel separator unit, consisting of gated sample and hold circuits, and the three outputs are then fed to a minicomputer or microprocessor which calculates $T_G$ from the above algorithm and outputs the temperature. It appears feasible to use miniature choppers, commercially available, that would give a measuring sequence time of 1 msec, thus providing temperaure measurements to 1 kHz for studying fluctuations.
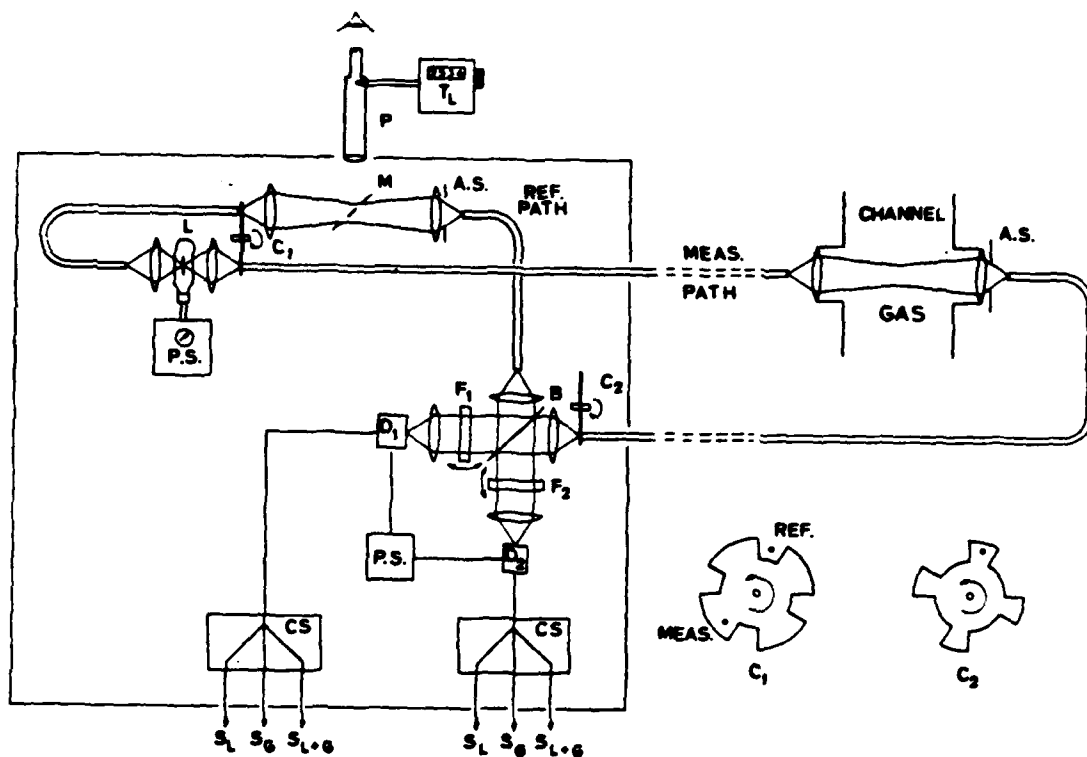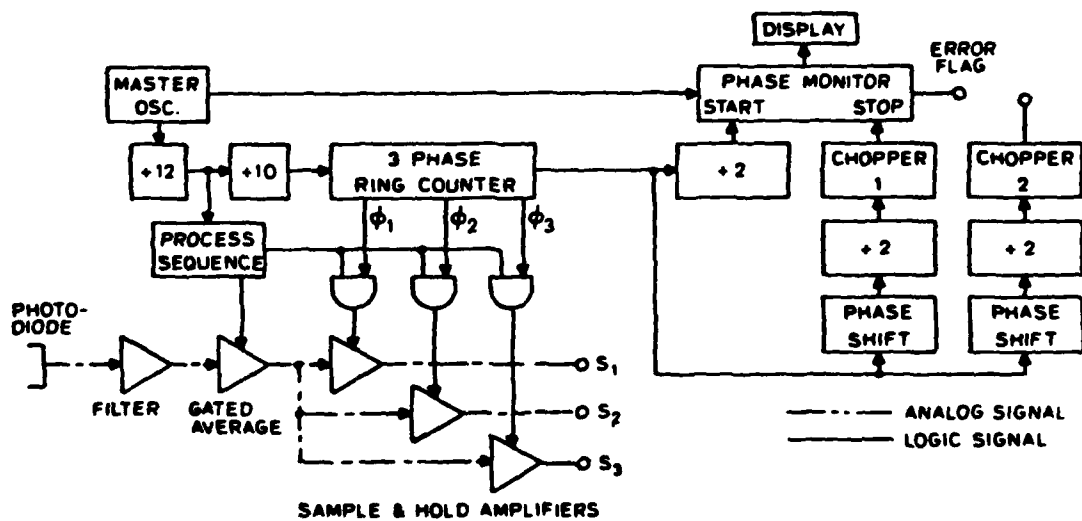
Figure 16a. Schematic of optical system.



Figure 16b. Schematic of electronic system.

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The mirror M, shown in the reference path, is a high reflectivity front surface mirror which can be inserted when required to measure the brightness temperature of the lamp with a standard calibrated pyrometer.

Traditionally, in the line-reversal technique, a grating monochromator has been used for spectral selection, but this leads to a cumbersome setup. For applications involving heavy seed concentrations and large path lengths, where the spectral lines are very broad, we plan to use narrow band $(\lesssim 3 \text{ Å})$ dielectric filters shown as $F_1$, $F_2$ in Fig. 16a, which can be tuned sufficiently by tilting. For applications involving low seed concentrations and shorter path lengths, where the spectral lines are narrow, higher resolution is necessary. For this purpose we plan to use a tunable Fabry-Perot etalon in combination with a broader band dielectric filer.

Certain conditions must be met to maximize the measurement accuracy in using this technique. First, the lamp temperature should be set as close to the average gas temperature as possible, so as to minimize the sensitivity to error or noise in the three signals when calculating from the above algorithm. The maximum temperature of tungsten ribbon lamps, consistent with adequate long-term stability of their calibration, is about 2500 K, so that only for gas temperatures higher than this is one obliged to extrapolate significantly.

The second condition involves the optical depth of the gases, which is a function of the alkali metal seed concentration, the optical path length, and the wavelength relative to line center of the resonance line. To obtain accurate measurements, the optical depth, $\exp(-\alpha_\lambda \ell)$ (where $\alpha_\lambda$ is the absorption coefficient and $\ell$ is the path length), should be of order unity, so that the three signals in the denominator of the logarithm in the above formula, are of similar magnitude. With sodium or potasium seed, and gases or plasmas of laboratory scale ($\sim 10$ cm), this condition can be met with conveniently low mole fractions of seed $\sim 0.01 - 0.1\%$.

Another question related to the optical depth and seed concentration is the self-reversal of the emission line in flows where there is a significant temperature profile, e.g., where the thermal boundary layers have an appreciable thickness relative to that of the core. In such cases, a measurement

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through the whole body of the gas gives some line-of-sight average temperature which is difficult to interpret. One method for obtaining the core temperature in this case is to detune into the wing of the emission line, where the optical depth is ~ 0.5, and apply a correction to the apparent measured temperature obained from calculations based on an estimated boundary layer temperature profile. An alternative technique, which we propose to explore, is to insert the transmitting and receiving fiber optic probes into the flow. The thermal boundary layers formed on the ends of the probes would be very thin, and by ganging the probes together, with a separation small compared to the flow dimension, it should be possible to measure the local temperature (and hence temperature profiles by translating the probes). Since the path length is reduced, it would be necessary to increase the seed concentration to maintain an adequate optical depth.

Traditionally, sodium seed has been used in the line-reversal technique, with measurements made close to the shorter of the two resonance lines at 589.0, 589.6 nm, using a photomultiplier as detector. We propose to explore the use of potassium seed whose resonance lines lie at 766.5, 769.9 nm, where silicon photodiodes have their maximum quantum efficiency (~ 70%). Such diodes are smaller, cheaper and, importantly, have a more stable sensitivity than photomultipliers, and are now available with integral amplifiers.

To this point, the discussion has been directed at temperature measurements in clean combustion flows, and a single filter and detector channel would suffice for this case. For particulate laden flows, e.g., sooty flames or solid-fuel rocket exhausts, the conventional line-reversal technique is invalidated by scattering, absorption and thermal emission from the particles, and there is need of a modified technique for such applications. It can be shown that by making measurements, as described above, simultaneously at two wavelengths, one can derive a formula which gives the gas temperature, as well as information about the particles, in terms of the three signals at the two wavelengths. One wavelength is chosen on, or close to a resonance line of the seed as discussed above; the other is made at a wavelength detuned off the line, where the seed emission/absorption is negligible compared with that due to the particles. This is accomplished by the second filter and detector channel shown in Fig. 16a.

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## Scientific Merit

The merits of this work are several-fold. First, as noted above, there is a need for a packaged, versatile instrument that can be used remotely to measure temperature in a variety of combustion flows, with a direct readout. Second, the instrument will have a resolving time of 1 msec which will allow temperature fluctuations to be followed to a frequency of the order of 1 kHz. Third, with further work, the instrument can be extended to measure temperature in particulate-laden flows provided the optical depth due to the particles is not too great.

## Status Report

The optical system has been designed and the components, including lamp, fibers, lenses, beam splitter, detector and choppers assembled. For application to combustion flows lightly seeded with Na or K, the resonance lines will be relatively narrow. Consequently, to obtain sufficient spectral resolution we have chosen to use a piezo-electrically tuned Fabry-Perot etalon as the dispersing element rather than a conventional narrow band filter which would not be narrow enough.

We have taken delivery of a custom-designed Fabry-Perot etalon and have tested its performance using a He-Ne laser. It has a free-spectral range of 18 Å and a finesse of ∼ 75 so that the passband is ∼ 0.25 Å with a transmission of ∼ 70%.

The lower trace in Fig. 17a shows the transmission of the Fabry-Perot as it is scanned across two adjacent modes (1 free spectral range) 18 Å apart. The upper trace shows the ramp voltage applied to the etalon. Because of the relatively high thermal expansion coefficient of the piezoelectric material, it is necessary to provide the Fabry-Perot etalon with a temperature controlled enclosure. The enclosure, with feedback-stabilized heater control has been designed, constructed and tested satisfactorily.

Because the Fabry-Perot is a multimode device, acting as a comb filter, with passbands every 18 Å, it is necessary to use it in conjunction with a subsidiary fixed filter to isolate a single mode. For this purpose we have

Figure 17a   Lower Trace:  Fabry-Perot
response to He-Ne laser showing two
adjunct modes 18 apart.
Upper Trace:  Ramp voltage applied
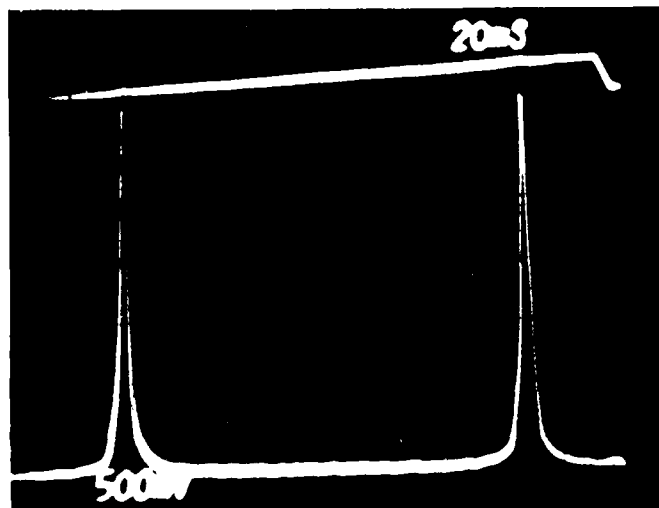to scan Fabry-Perot.



Figure 17b   Lower Trace:  Response of
Fabry-Perot-filter combustion to tungsten
lamp radiation.  Markers show position
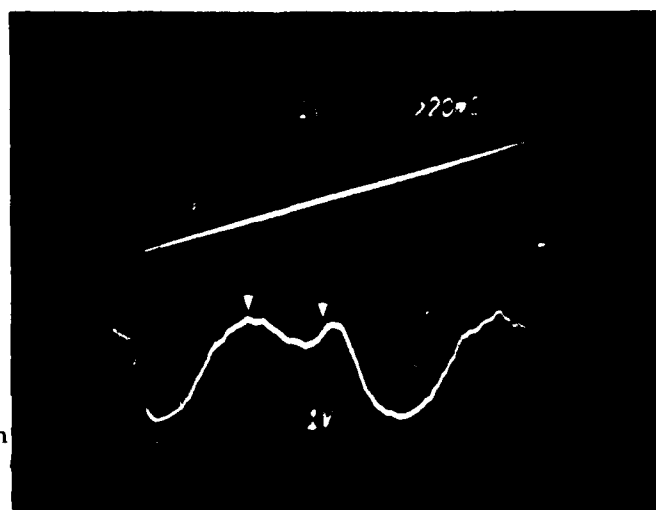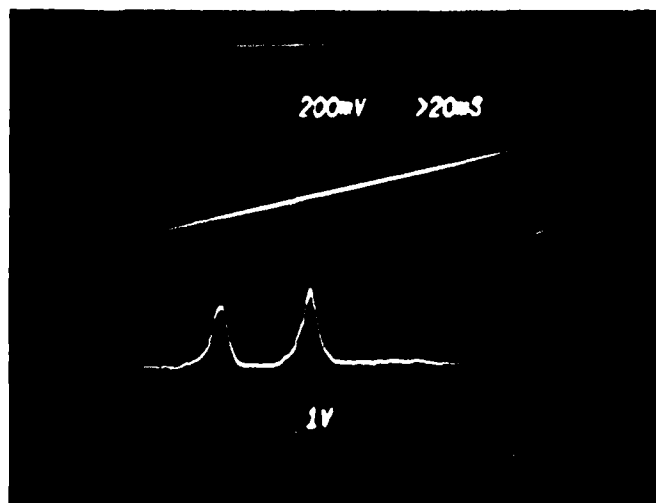of Na resonance lines at 5890, 5896 Å



Figure 17c   Lower Trace:  Response
of Fabry-Perot-filter combustion
to Na resonance lines from acetylene
air burner

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specified a custom-designed, three-cavity dielectric filter having a full
width to half-maximum bandwidth of 12 Å, centered at 5892 Å, midway between
the Na resonance lines. The passband can be tuned to shorter wavelengths by
tilting the filter, if this is necessary. The lower trace in Fig. 17b shows
the transmission of thge Fabry-Perot filter combination to black-body radi-
ation of a tungsten strip lamp at $T_L$ = 2180K. The arrows indicate the
positions of the Na resonance lines at 5890, 5896 Å. The filter profile is
not as flat-topped as we should like, but will be perfectly adequate for the
intended use.

For preliminary tests a Perkin-Elmer acetylene slot burner, with facility
for sodium aerosol seeding is being used. The necessary flow control and
monitoring equipment has been constructed. The lower trace in Fig. 17c shows
the response of the Fabry-Perot filter combination as it is scanned across the
Na resonance lines from the seeded flame.

Preliminary tests of the total system (excluding the signal processing
electronics) have been made. Figures 18a - c show the detector response $S_{L+G}$
due to both the tungsten lamp and the seeded acetylene-air flame as the Fabry-
Perot is scanned over about 30 Å, rather more than one free spectral range.
In Fig. 18a the lamp temperature is $T_L$ ~ 2060K, somewhat less than the gas
temperature, and the emission peaks due to the Na resonance lines are clearly
visible. In Fig. 18b $T_L$ has been increased to 2180K, very close to the gas
temperature, and the emission lines are now invisible against the background
lamp radiation. In Fig. 18c the lamp temperature has been increased to 2240K,
above the gas temperature and the resonance lines are now visible as
absorption dips against the continuum from the lamp.

These preliminary results indicate that the Fabry-Perot filter combination
will be a satisfactory spectral selection element for the instrument. Future
work will be directed towards optimizing the design of the signal processing
electronics to test the whole concept of obtaining a fast automatic readout of
temperature.

Figure 18a  Lower Trace:  Response
of Fabry-Perot-filter combustion
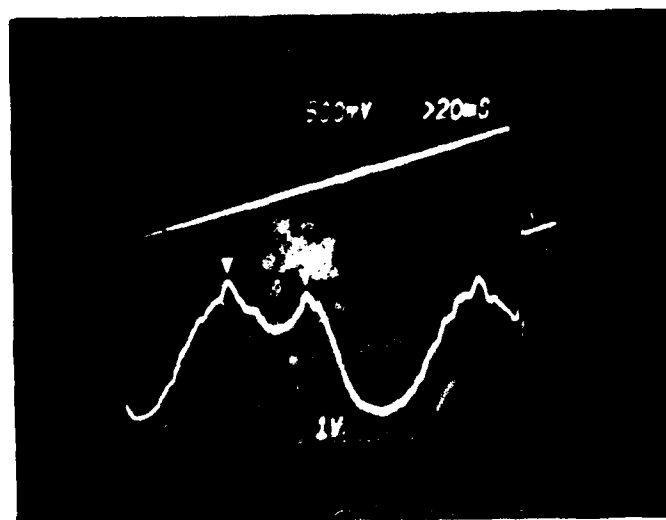to lamp transilluminating flame.
$T_L$ = 2060 K   $T_G$ = 2180 K



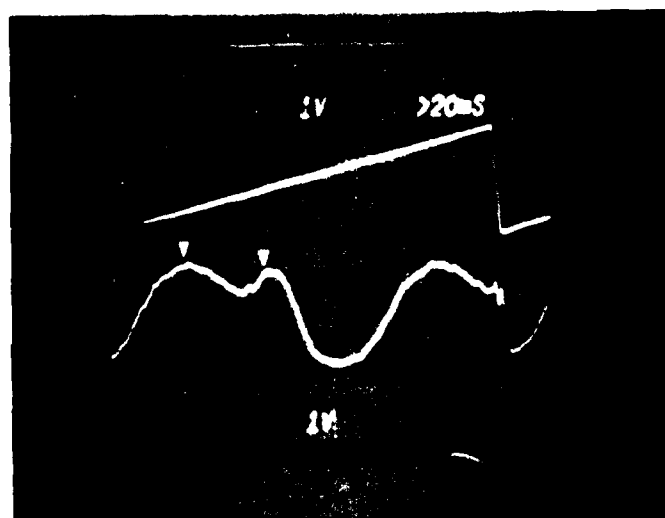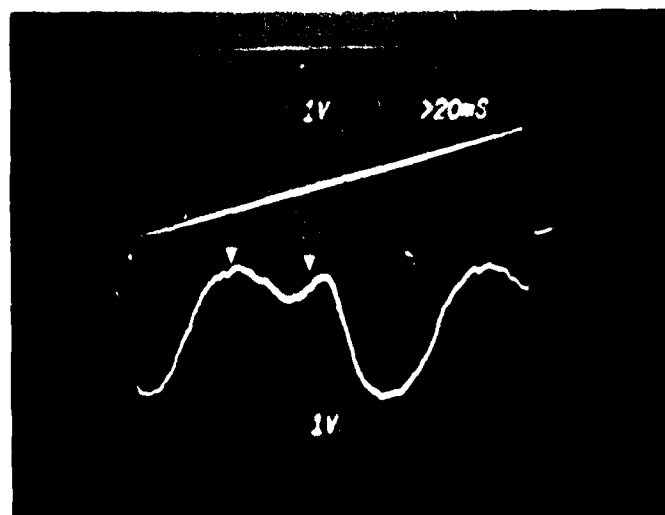Figure 18b.  Lower Trace:  As above
but with $T_L$ = $T_G$ = 2180 K



Figure 18c.Lower Trace:  As above
but with $T_L$ = 2240 K

## Publications

The following paper has been accepted for presentation at the "Sixth Symposium on Temperature; Its Measurement and Control in Science and Industry," organized by the National Bureau of Standards, March 1982.

"A Packaged, Fiber-Optic Spectroradiometer for High Temperature Gases with Automatic Readout," by S. A. Self, P. H. Paul and P. Young.

## Personnel

S. A. Self            Adjunct Professor, Mechanical Engineering

P. Young            Graduate Student, Mechanical Engineering

## 2.5 Quantitative Flow Visualization

### Introduction

The utility of flow visualization as a diagnostic in studies of fluid mechanics and gas dynamics is well established. However, most visualization techniques are qualitative and are based on line-of-sight approaches which are poorly suited for flows with three-dimensional characteristics. With the recent development of laser-based light scattering techniques, it should be possible to obtain temporally resolved quantitative records of flow properties throughout a plane (and ultimately throughout a volume) using sheet illumination and a scattering technique such as Raman, fluorescence or Mie scattering. In fact, pioneering work along these lines using Mie scattering from seeded particles was initiated at Yale a few years ago, and significant progress has recently been reported.

Work along similar lines has been initiated at Stanford during this past year. The major distinctions between the previous work at Yale and that at Stanford, as we envision the Stanford project at present, are: (1) we plan to use scattering techniques which are sensitive to species concentration in reacting flows, such as fluorescence or near-resonant Raman, rather than Mie scattering; (2) we hope to record at higher repetition rates, thereby allowing the possibility of studying the real-time evolution of various fluid mechanical structures; (3) the flows we wish to investigate are a two-dimensional shear flow and other simple laboratory combustion flows; and (4) we

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plan to use a multichannel plate image intensifier and photodiode array detector rather than an intensified vidicon.

The advantage of fluorescence or near-resonant Raman is obvious in that the gas is tagged at a molecular level, thereby avoiding problems inherent with particulate seeding. The disadvantage of fluorescence has been that quenching must be well understood for the experimental conditions employed. We believe this can be handled through calibration, or alternatively by using a variation of the process, known as off-resonance fluorescence, which is weaker but serves to eliminate or at least minimize the dependence of signal level on quenching parameters. With regard to faster recording, we will utilize recently developed fast multichannel plate image intensifiers and photodiode array detectors, as well as high-speed photography to provide qualitative displays. Fast recording will also require higher laser intensities (together with high repetition rates) and hence may require development of a special high-repetition rate, pulsed tunable laser source.

The Stanford approach, as to be applied to a 2-d shear flow, is illustrated in Fig. 19. The flow will be illuminated by a sheet of light from a tunable laser source (cw dye laser, YAG-pumped dye laser, or new high-repetition rate tunable laser source), and one or more rectangular detector arrays preceded by one or two stages of image intensification will be used to monitor specific species. We plan to begin with iodine, because of our experience with that compound, and a room temperature flow. Variations of fluorescence and near-resonant Raman will be evaluated as scattering processes. Once we have further experience with these candidate processes in iodine, we plan to apply the optimum process techniques in a simple laboratory flame, tentatively to measure OH. Subsequently, we will investigate means to record multiple species, and other properties such as density and temperature. In addition, once we have a suitable high-repetition rate source and detection system, we plan to work toward rapid scanning of the illuminated plane to yield three-dimensional recording of species concentrations. We wish to emphasize that these are long-term research objectives which involve several technical challenges and hence will extend beyond the next year of current support.
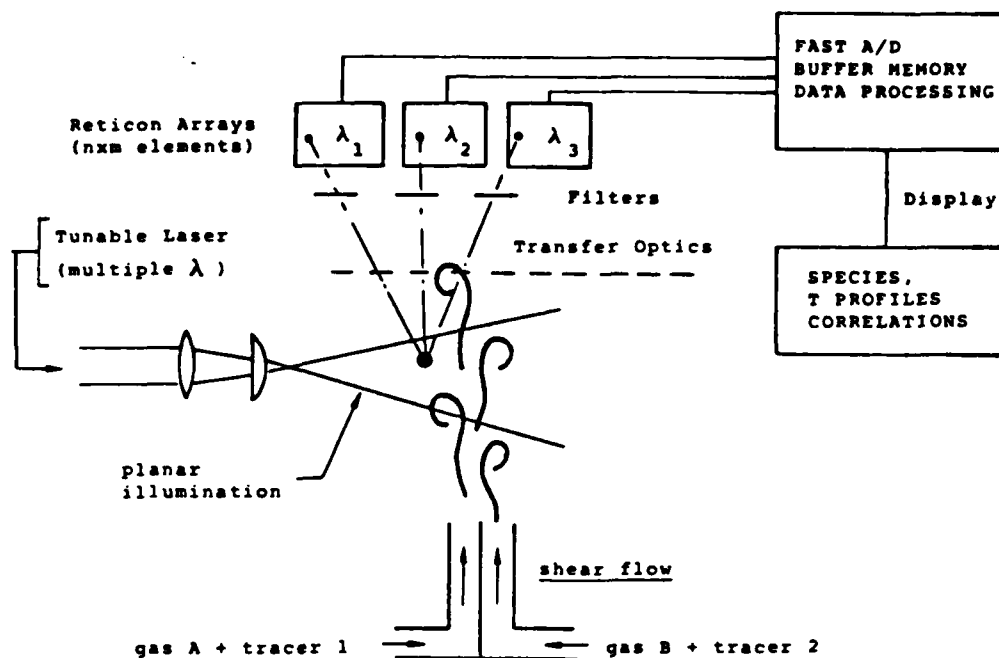
Figure 19. Quantitative flow visualization.

Objective:      Develop techniques for temporally resolved
                2-D and 3-D measurements of species, temperature
                and velocity
Status:         First-generation experiment under construction
                (fluorescence from iodine in a plane)
Future:         Extend to: multiple species, density/temperature,
                and velocity; 3-d
Significance:   Potential major impact on fluid mechanics
                research.

It should be noted that this effort to develop a quantitative flow visualization scheme complements other research in this program, particularly the development of tomography (Section 2.3) for measurements in a plane and fluorescence (also with $I_2$) for measurements of density along a line near an evaporating droplet (Section 2.7), as well as the work with fiber optic absorption probes to measure local species concentrations (Section 2.1). Thus it should be possible to perform several comparative studies using these various techniques in selected flows.

## Scientific Merit

With the exception of the work by Chang at Yale, which has until now emphasized Mie scattering, we believe that the Stanford research on quantitative flow visualization is unique. This is difficult and expensive research, requiring combined advances in laser sources, the physics of laser scattering, image intensification, radiation detection, and data processing, but the significant potential impact of this work on the disciplines of fluid mechanics and combustion justifies the effort. The type of time-resolved, three-dimensional information which we believe can ultimately be generated using our approach is not available by any other current technique. We expect that the combination of facilities involved in this project, once assembled, will be unique, particularly in the fluid mechanics and combustion communities.

## Status Report

The initial phase of this project has entailed experimental design and selection of components to provide a complete integrated system from the laser source, illumination and detection optics, detection system, digitizing and data storage systems and computer interfacing. Highlights of this work include the following:

1. Laboratory studies o iodine seeded jet flows have been completed (see Section 2.7) to investigate laser-induced fluorescence and several related processes to determine an optimum scattering process. Based on results in iodine, off-resonant fluorescence appears to be the optimum choice. Current work involves: studying the influence of the non-resonance (detuning) on efficiency and

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linearity and investigating the applicability of this process to other species of interest in combustion flows.

2. Tunable cw dye laser and pulsed dye laser systems have been specified, purchased and set up in the laboratory. (These same systems will also be used for other projects in this program.) The pulsed laser system is a Nd:YAG-pumped dye laser operable up to 20 Hz (0.7 J at 1.06 $\mu$m). This should be adequate for our immediate needs, but we have also been investigating high-repetition-rate pulsed tunable laser systems which will operate at 10 kHz and above for real-time flow visualizations.

3. A dedicated laboratory microcomputer (DEC 11/23 Declab) has been specified, purchased and installed in the laboratory. The system is now operational and modifications are in progress to extend the A/D rate to 125 kHz. This system will be suitable for the first phase of our work, but ultimately a larger machine with faster A/D capability will be needed for high-repetition-rate observations.

4. Various rectangular array detectors have been investigated with regard to sensitivity, readout rate, dynamic range, spatial resolution, reliability, cost and computer compatibility. Two systems were selected and have now been delivered, both based on 100 x 100 photodiode arrays by EG & G (MC 520 camera with RS 520 controller and 8-bit A/D option). One system is currently being mated to an ITT multichannel plate intensifier (variable luminous gain to $10^6$), and the other (unintensified) is currently in use to facilitate work on interfacing the camera to the computer.

5. A first-generation flow system has been designed and partially assembled. This is a facility with provisions to study a variety of flows including a 2-D shear flow, flow over a circular cylinder, and an axisymmetric jet. Flow rate, iodine seed rate and pressure will be variable.


Publications and Presentations

None

Personnel

Ronald K. Hanson          Professor, Mechanical Engineering

Robert Howe               Research Physicist, Mechanical Engineering

Bernhardt Hiller          Graduate Student, Mechanical Engineering


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## 2.6 Application of Diagnostic Techniques to Turbulent Reacting Flows

### Introduction

A principal motivation for the development of advanced diagnostic techniques for reactive flows is the need to characterize flow fields in practical combustion devices. Flow field measurements are useful not only in understanding combustor performance but also in providing information useful to combustion modellers. One component of the present overall program is the development of laboratory-scale facilities which simulate essential features of practical combustion devices and the application of various diagnostic techniques to such flows. These laboratory-scale devices will be used to evaluate new diagnostic techniques and to obtain data on the structure of turbulent reacting flows which will guide the further development of new techniques and also provide input to reacting flow models.

To date, an atmospheric-pressure, two-dimensional shear flow facility, Fig. 20, has been constructed. This facility provides a means of simulating fuel-air mixing regions in air-breathing engines. The non-reacting flow field in this facility has been characterized by conventional diagnostic methods, such as hot wire anemometry, and measurements will be extended to isothermal and non-isothermal turbulent reacting flows. Upon completion of these measurements, a well-characterized reacting flow will be available for evaluation and validation of newly-developed diagnostic techniques. In addition, the data obtained from the characterization tests and from the diagnostic validation tests will provide useful new fundamental information on the coupling between fluid dynamics and chemistry in turbulent reacting flows.

### Scientific Merit

The evaluation and validation of advanced diagnostic techniques under practical combustion conditions is an important final step prior to transfer of technology to outside users. Reacting flow field data obtained in this study will provide important input to combustion model development, particularly in regard to incorporating appropriate sub-models for turbulence-chemistry interaction.
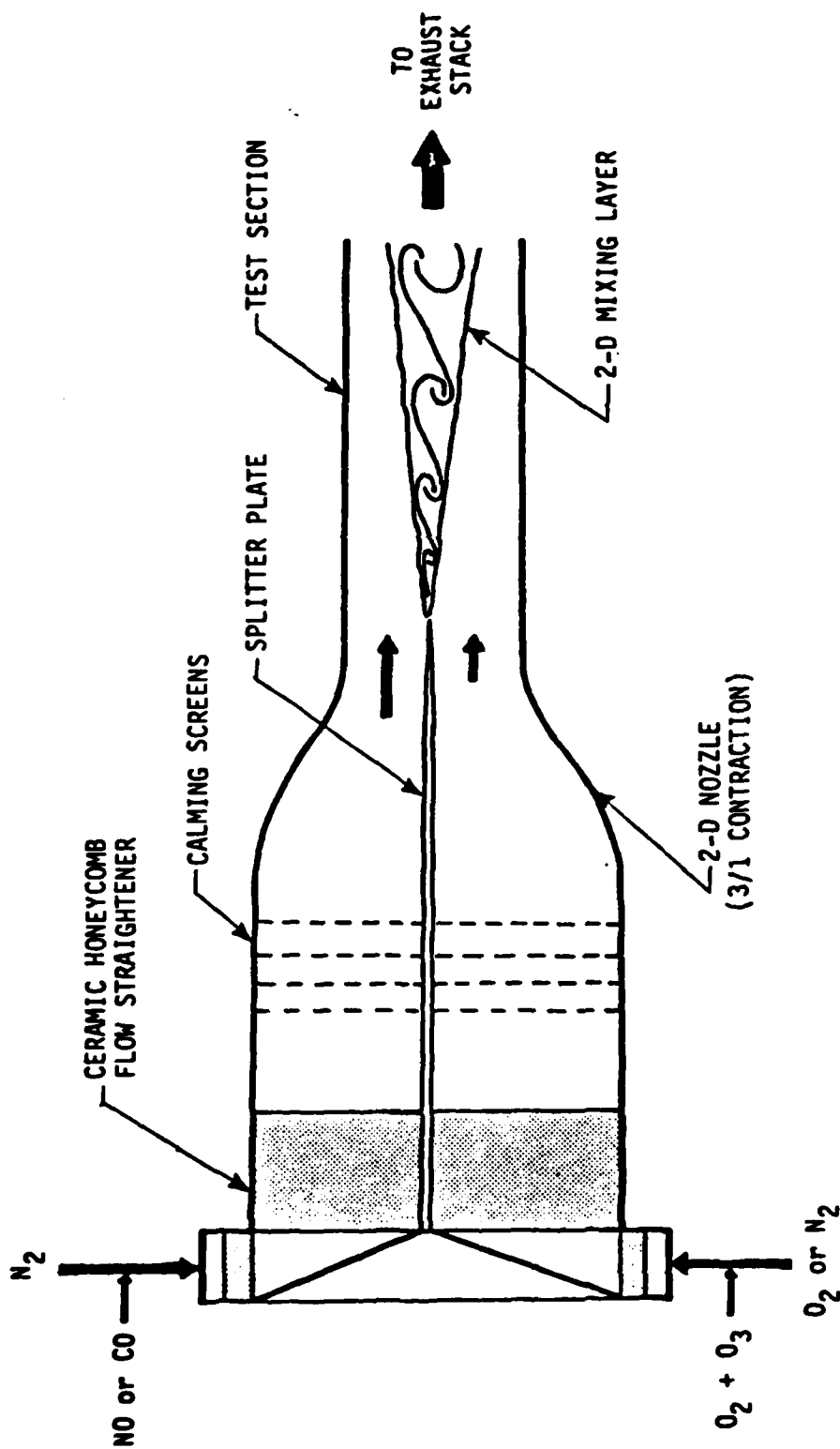
37

Figure 20. 2-D reacting shear flow facility.

During the past year, flow field characterization in the two-dimensional shear flow facility under non-reacting conditions was completed, and measurements on reacting flows were initiated.

## Publications and Presentations

None

## Personnel

| | |
|---|---|
| C. T. Bowman | Professor, Mechanical Engineering |
| Stephen M. Masutani | Graduate Student, Mechanical Engineering |

## 2.7 Concentration Measurements in Evaporating Flows

### Introduction

A wide variety of combustion devices rely for their operation on the evaporation and mixing of liquid droplets in the presence of turbulent flow. For example it has been observed that ignition delay times in gas turbine combustors may often be correlated with droplet evaporation times. Results of this sort have motivated many investigators to incorporate the evaporation process into models of turbulent combustion. However, the behavior of droplets in a turbulent combusting flow is extremely complex involving simultaneous heat, mass and momentum transfer. The evaporation process is influenced by fuel type and chemistry, ambient gas composition, gas temperature and pressure, the droplet size distribution, droplet spacing, and the relative velocity between the droplet and surrounding gas. Consequently, models of spray combustion are often required to compute very detailed results for combusting flow fields without benefit of experimental data for comparison.

The aim of the research here is to develop new diagnostic techniques and to demonstrate their application to measurements of droplet evaporation rates under controlled laboratory conditions. More specifically, our goal is to develop a spatially and temporally resolved technique for measuring the

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concentration field around evaporating drops in an unsteady flow (Fig. 21).
The technique requires high spatial resolution as well as a wide dynamic range
to accommodate flows in which the full range of concentration fluctuations is
encountered. At the present time laser-induced fluorescence using iodine as a
fluorescent seed material appears to be the best choice for the concentration
measurements. Fluorescence has significant advantages over other techniques
for measuring concentration. Absorption techniques usually involve
integration of the concentration along an optical path. Aspirating probes
disturb the flow and cannot achieve either the temporal or spatial resolution
of the fluorescence technique.

We would like to develop the concept of using laser anemometry together
with laser-induced fluorescence of a dye added to the liquid to measure liquid
and gas phases in a turbulent droplet-laden flow. Laser anemometry has well
known advantages over conventional hot wire anemometry for measuring fluid
velocities. Addition of a fluorescent dye to the liquid provides an unambig-
uous method for discriminating between droplets and gas phase seed particles
and offers significant advantages over methods based on selective seeding or
particle visibility. The obvious disadvantage is the need to add a dye to the
evaporating liquid which may not be possible in some practical studies of
spray combustion.

Verification of the techniques developed for these studies will be carried
out in a unique flow facility designed to operate over a wide range of
pressure, particularly subatmospheric pressure appropriate to diagnostic
techniques based on laser-induced fluorescence. This feature of the facility
will play a central role in the verification studies of laser-based diagnos-
tics in which the ambient pressure is a major limiting factor.


Scientific Merit

Improved knowledge of the process by which molecules leave the liquid
state of a fuel droplet and diffuse or mix with the gas environment is needed
in order to better understand the physical processes of spray combustion. In
particular, one needs multipoint measurements of the vapor concentration field
in the neighborhood of a droplet evaporating in an unsteady flow. At present,

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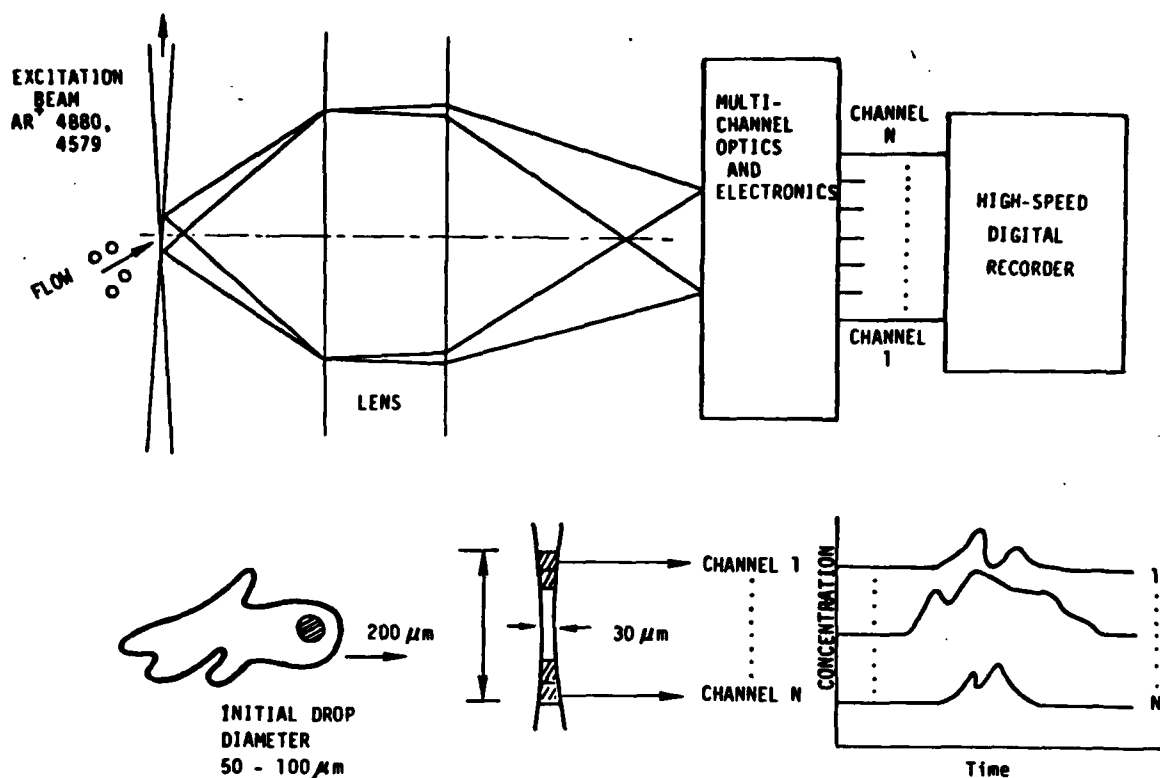
APPLICATION: Droplet evaporation studies in laminar and turbulent heated flows

SIGNIFICANCE: Improved, laser-based diagnostics offer potential for significant advances in understanding of reacting, two-phase flows

Figure 21. Multipoint concentration measurements around a droplet.

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no technique has been developed to give this information. The aim of the present research is to develop a spatially and temporally resolved technique based on laser induced fluorescence for measuring the concentration field around evaporating drops in an unsteady flow.

## Status Report

Verification of the techniques developed under this program will be carried out in a small blowdown flow facility presently under construction and shown schematically in Fig. 22. The facility is now largely complete and major specifications are listed below.

| | |
|---|---|
| Test section | - 10 cm x 15 cm x 40 cm |
| Running time | - 5 - 10 sec |
| Pressure | - 0.15 to 15 atmospheres |
| Velocity | - 10 to $10^3$ cm/sec |
| Reynolds Number | - 10 to $10^5$ cm$^{-1}$ |

The gas flow will be supplied from a high pressure reservoir and droplets from an aerosol generator will be introduced into the flow downstream of the main control valve which sets the test section mass flow. The test section will have glass windows on all four sides to provide full optical access to the flow and will be mounted vertically adjacent to an optical table which supports the measurement apparatus.

The flow is supplied by high pressure bottles and the test section exhausts into a 40 ft$^3$ volume which is at hard vacuum pressure when the run is initiated. We have acquired four sections of a shock tube from NASA Ames for this purpose. These sections are 12-inch diameter flanged, stainless steel pipes 8 feet long. These sections have recently been installed in a 10 foot concrete-lined pit in the laboratory which will house the droplet evaporation test rig.

Work currently in progress includes fabrication of the test section and its associated turbulence suppression section. This includes the purchase and
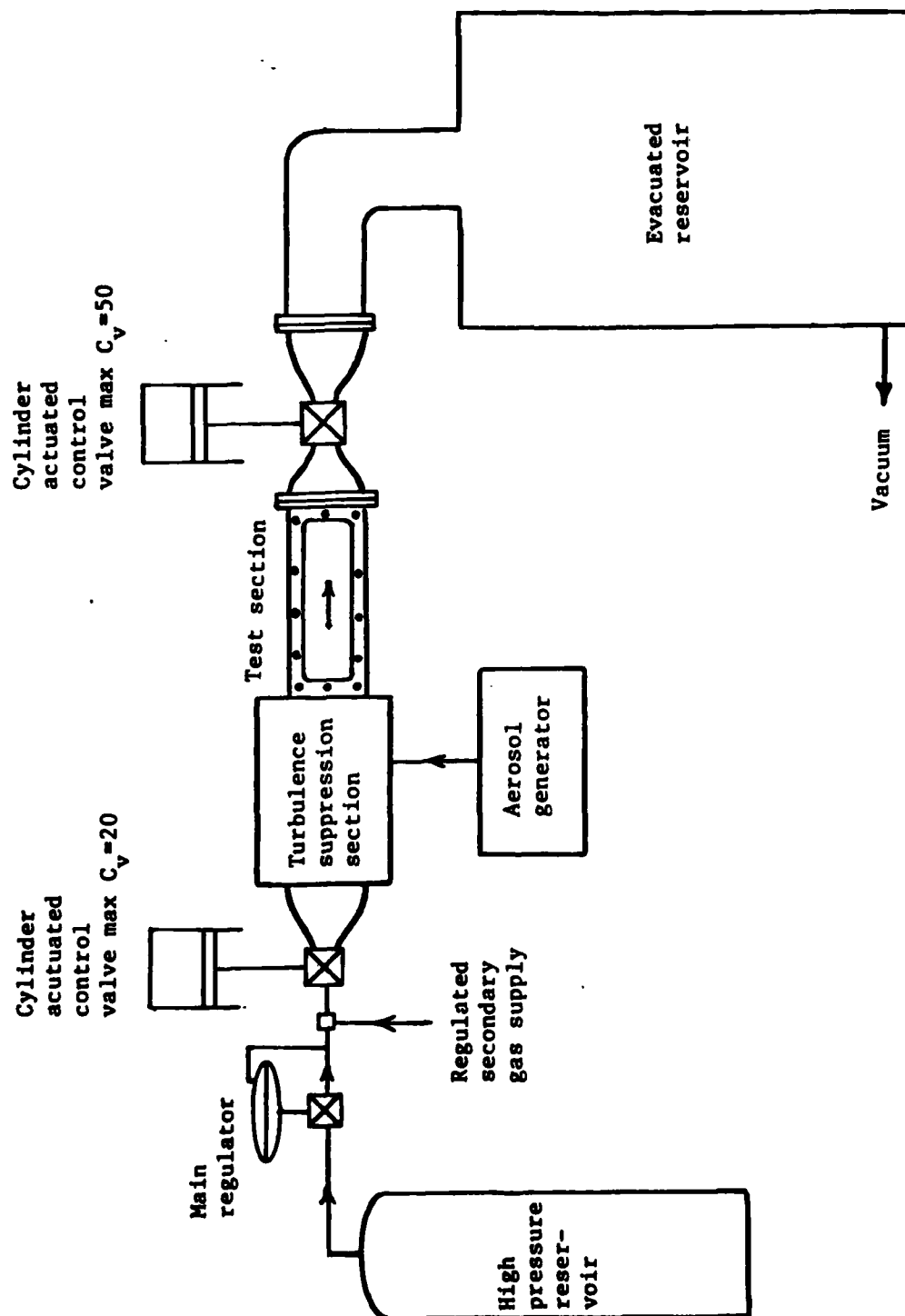
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Figure 22. Droplet evaporation test rig.

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assembly of a fast opening main valve, dome regulator, schlieren quality
windows and a two-dimensional traverse.

Thus far, the setup of equipment for the laser diagnostic scheme for the
multipoint concentration measurements is being kept physically separate from
the setup for the associated flow facility, and at this time they are in fact
in adjacent rooms. This is because the anticipated time required to construct
the flow facility is considerably greater than the time needed to assemble the
equipment for the measurement scheme, and thus the physical separation allows
work to progress on the technique simultaneously with efforts to design and
construct the flow facility.

The equipment acquired to conduct the study consists of a Spectra-Physics
5-Watt Argon-Ion Laser, a Spectra-Physics Etalon for the Argon-Ion Laser, a
Newport Research 4' x 8' Optical Table, a Newport Research Beam Steering
Instrument, a TSI Particle Generator, and a TSI Monodisperse Aerosol
Generator. Most of these components were not immediately available and it was
necessary to wait several months for their delivery. While we were awaiting
delivery of the equipment, preparations were made in the laboratory to provide
appropriate service for the installation of the argon-ion laser, in the form
of electrical power and a source/disposal arrangement for cooling water, and
to exhaust small amounts of toxic gases that we planned to use in the exper-
iments.

On delivery of the equipment and following the initial set-up period and
familiarization with their operation, we proceeded to turn our attention to
the problem of localizing and imaging the sequence of small droplets produced
by the monodisperse aerosol generator. Because the aerosol generator produces
a regular sequence of droplets of a given size in step with an applied square
wave input signal, we were able to strobe the light source and fix the droplet
image in the field of view. In attempting to image the droplets, we are using
coherent light from the argon-ion laser because we are primarily interested in
studying the vapor cloud that forms in the immedia e vicinity of the droplet
rather than the droplet itself.

Prospects for studying the vapor cloud surrounding an evaporating droplet
by making use of fluorescence have been significantly enhanced by recent

results which have been obtained in one of our related studies. In this work a two-dimensional density map of a streamwise cross-section of an axisymmetric supersonic jet of nitrogen was obtained using 0.3 torr of iodine to seed the flow. This method (near-resonant scattering) makes use of the fact that one of the absorption lines of iodine lies very close to the strong 514.5 nm (green) output of the argon-ion laser, and by use of an etalon, one is able to tune across the iodine absorption line and produce a scattered signal with a character that varies from one having the behavior of fluorescence (zero shift from line center) to one having more of the character of Raman scattering ( a detuning of 3 GHz in this case). The fluorescence signal (zero detuning) suffers from quenching as the pressure changes in a compressible flow, while the near-resonant signal (3 GHz detuning) is less sensitive to quenching.

We first encountered the effect as an experimental observation. More recently, we have been able to develop a theory, based on a rate equation model for the iodine molecule, that helps to explain the origin of the effect. We found that when the detuning greatly exceeds the Doppler width, the decrease in the fluoresence signal amplitude with increasing pressure as a result of quenching, is just cancelled by the increase in the signal amplitude due to broadening of the wings of the true profile with increasing pressure. When this cancellation is achieved, the fluorescence signal is essentially proportional to the iodine concentration alone. The theory successfully defines the conditions under which the cancellation is expected to occur and has opened up possibilities for making the measurement in still new ways.

For the case we studied, we found that the peak intensity of the near-resonant signal was only 20 times weaker than the peak intensity of the corresponding fluorescent signal and therefore a photograph of the image of the jet using the signal was entirely feasible. The cross-section of the axisymmetric jet was illuminated by a sheet of argon-ion laser light and a 10-sec time-exposure photograph of the cross section of the flow (in color) was obtained. The correspondence between the intensity distribution on the photograph and the expected density distribution in a supersonic jet (including the first normal shock wave) is quite striking when compared with the less easily interpreted intensity distribution seen on a photograph using the fluorescence signal.

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## Personnel

| | |
|---|---|
| D. Baganoff | Professor, Aeronautics/Astronautics<br>(New techniques, droplet evaporation) |
| B. J. Cantwell | Professor, Aeronautics/Astronautics<br>(Droplet evaporation, diagnostic<br>application) |
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| D. R. Neal | Graduate Student<br>Aeronautics/Astronautics |

## 2.8 New Techniques

In addition to those projects already summarized in Sections 2.1 - 2.7, some effort has been directed toward investigation of new diagnostic concepts. An example of work in this category is our research during the past year with off-resonant fluorescence and Raman scattering. Interest in this physical process actually resulted from work (supervised by Prof. Baganoff; see Section 2.7) to investigate saturated fluorescence for species measurements. The off-resonant techniques involve, in practice, simply detuning the laser excitation wavelength from the absorption wavelength normally used for laser-induced fluorescence. Procedures for selecting the optimum non-resonance are still under study, but recent results indicate that this process is superior to conventional resonant laser-induced fluorescence for purposes of providing a quenching-insensitive sensing process for flow visualization work. An indication of the improved insensitivity of the signal to pressure (density) is illustrated in Fig. 23. These results were obtained using a static cell configuration filled to variable $N_2$ pressure, but with a fixed iodine pressure, and with two values of excitation wavelength. It is clear that by detuning the laser by 3 GHz results in a much lower pressure dependence. These results as very encouraging although further study is needed to investigate applicability to other species.

We have also identified one other promising sensing concept which we have begun to invesigate. This is the so-called "ac-Stark effect" reported recently by Farrow and colleagues at Sandia Livermore. In essence, this is a crossed-beam absorption measurement involving a high-power pump beam and a lower-power probe (absorption) beam. The probe beam is tuned to an absorption
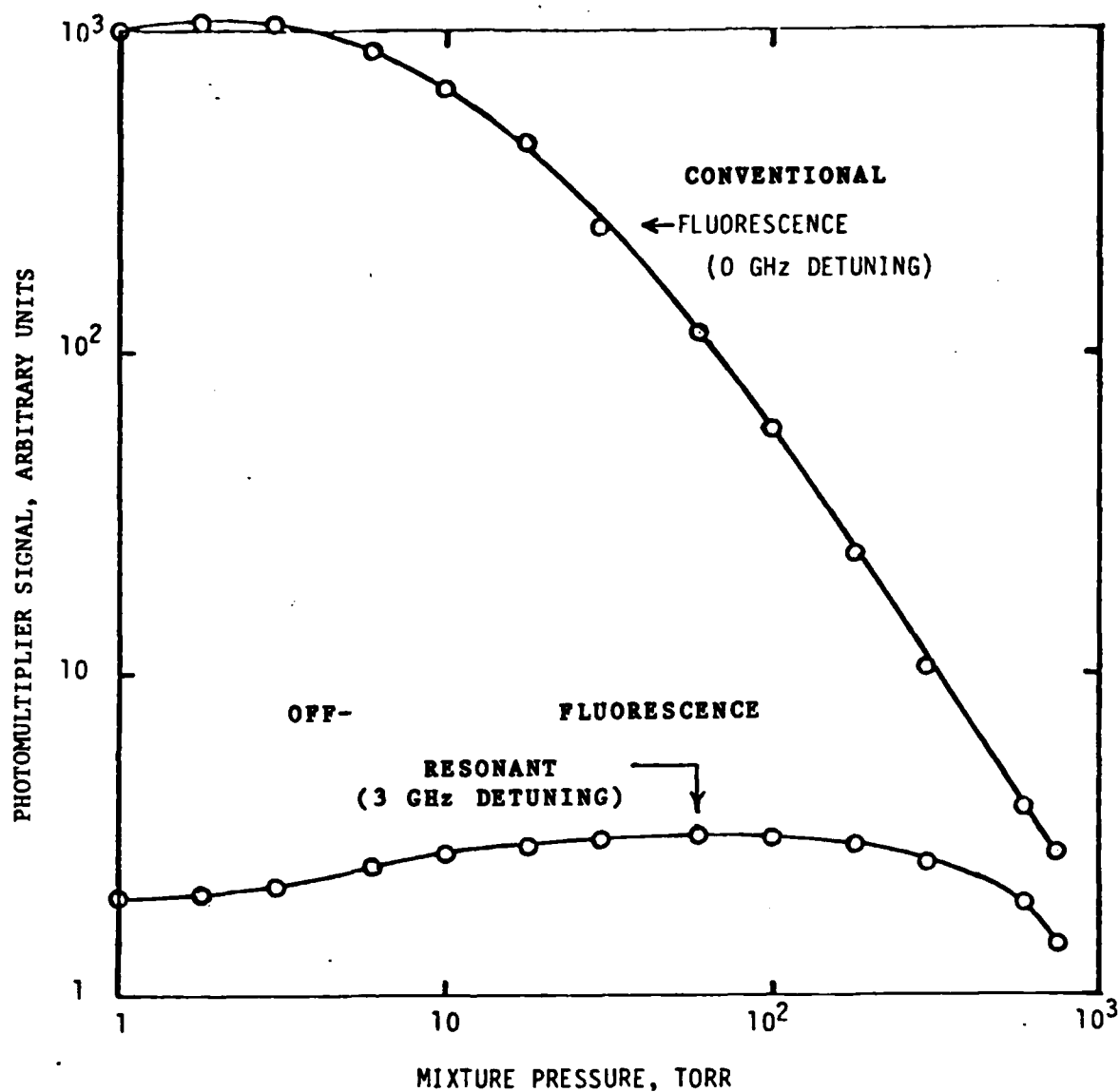
Figure 23. Reduced effects of quenching with increasing detuning between the frequency of the laser excitation and an absorption line in iodine; partial pressure of iodine = 0.3 torr; 514.5 mm argon-ion wavelength.

wavelength and the non-resonant pump beam is modulated at very high intensities to cause a shift in the absorption wavelength due to the high local electric fields. The modulation induced in the absorption beam can then be converted, if the absorption coefficient is known, to a local value of the absorbing species concentration in the overlap region of the two beams.

This effect has only recently been demonstrated and is not yet fully understood. We believe it is a promising concept and one that is particularly well suited to our interests and experience with tunable laser absorption spectroscopy. Although Farrow was limited to a fixed frequency $CO_2$ probe laser (and a coincident $NH_3$ absorption transition), the ideal arrangement to study lineshapes and shifts caused by this effect would be to employ a tunable, single-frequency probe beam such as either our diode laser (for infrared transitions) or our ring dye laser (for electronic transitions). Experiments are now being set up (under the direction of Professor Hanson) to investigate the ac-Stark effect and its variants. Both electronic and vibration-rotation transitions will be considered. Where possible tests will initially be done with room temperature gases where composition and pressure can be conveniently varied, prior to selection of a suitable demonstration in flame gases. The pump laser will be our Nd:YAG laser (Quanta-Ray, DCR-1A, 0.7 J/pulse at 1.06 $\mu$m), which is the same model as employed by Farrow.

We have already met with Farrow and his colleagues in order to ensure that our research is coordinated with efforts at Sandia Livermore.